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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

Edited by

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

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Yerkes Observatory of the University of Chicago

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SEPTEMBER 1928

27 CANIS MAJORIS: THE QUESTION OF ITS MASS - - - *Otto Struve* 109

SPECTROGRAPHIC STUDY OF THE MULTIPLE SYSTEM H0 212=13 CETI AB
Alexander Pogo 116

THE CONTOURS OF THE HYDROGEN LINES OF SIRIUS AND OF OTHER A-STARS
C. T. Elvey 145

THE PRESENCE OF PREDICTED IRON LINES IN THE SOLAR SPECTRUM AND THE TERMS IN THE ARC SPECTRUM OF IRON
Charlotte E. Moore and Henry Norris Russell 151

AN OPTICAL OSCILLOGRAPH - - - - - - - *Sinclair Smith* 165

ON THE VARIATION OF THE RADIAL VELOCITY OF TU CASSIOPEIAE
Roscoe F. Sanford 169

PREPARATION OF ABSTRACTS - - - - - - - - - 176

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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME LXVIII SEPTEMBER 1928 NUMBER 2

27 CANIS MAJORIS: THE QUESTION OF ITS MASS

By OTTO STRUVE

ABSTRACT

The spectroscopic binary 27 Canis Majoris has been regularly observed during the winter of 1927–28 with the one-prism Bruce spectrograph of the Yerkes Observatory. Observations were also made by Dr. F. J. Neubauer at the Chile station of the Lick Observatory and by Dr. R. F. Sanford at Mount Wilson Observatory.

The new spectrograms establish the fact that the period is very long, probably longer than 3.2 years and not longer than about 14 years. A short period of one day or less is not possible. The variation in the radial velocity exceeds 200 km/sec. Since the eccentricity cannot be very large, the total mass must be at least 1000 times that of the Sun.

The spectrum contains faint emission lines of hydrogen which are slightly variable in intensity. It is not possible, however, to explain the shifts of the absorption lines by the presence of emission. The velocity curve as well as other characteristics of this spectrum permit of no other interpretation than by orbital motion.

The large mass leads to serious theoretical difficulties. The absolute magnitude would be much greater than can reasonably be reconciled with the spectral type, or with the faintness of the detached lines. No explanation can at present be offered for this contradiction between the results of measurements of radial velocity and the requirements of theory.

Last year I commented[1] on the very unusual behavior of the spectroscopic binary 27 Canis Majoris. Its radial velocity undergoes changes over a range of more than 200 km/sec. and its period was believed to be at least 3.2 years, although there remained a slight possibility that it was equal to one day. We have since obtained twenty-four additional observations with the one-prism Bruce spectrograph of the Yerkes Observatory. These are shown in Table I, together with three observations made by Dr. R. F. Sanford at

[1] *Astrophysical Journal*, **65**, 273, 1927; **66**, 113, 1927.

Mount Wilson.[1] All the Yerkes measures since 1925 are plotted in Figure 1.

Additional spectrograms have also been obtained by Dr. F. J. Neubauer at the Chile station of the Lick Observatory. Through the courtesy of Dr. Aitken I am permitted to make use of these observations in advance of their detailed publication. On each of several nights Dr. Neubauer secured extended series of consecutive plates. The longest series consists of twelve spectrograms taken on December 30, 1927, between 0^h59^m8 and 8^h39^m6 G.C.T. Dr. Neu-

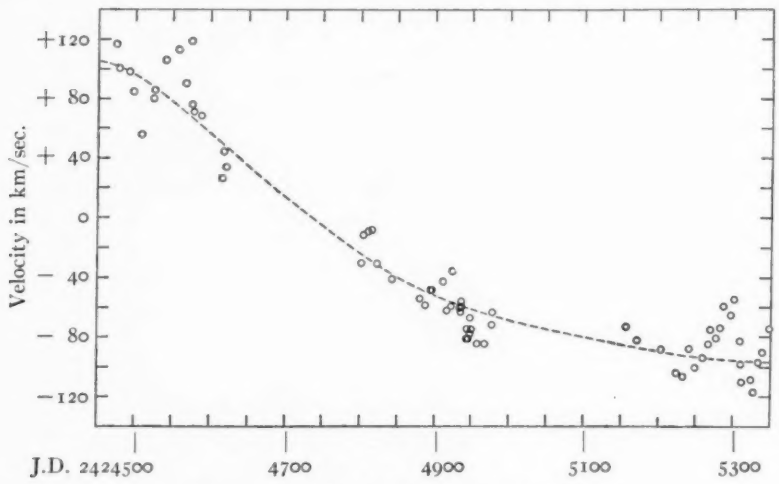


FIG. 1.—Radial velocities of 27 Canis Majoris

bauer has measured all of his plates and finds no progressive change in the velocity. His mean value closely agrees with that obtained at about the same time at the Yerkes Observatory. This result rules out all periods of the order of one day or shorter.

Exactly the same result is yielded by the combined Mount Wilson and Yerkes observations of December 8 and 9, 1927 (in Table I), and again from the Yerkes observations of January 21, 1928.

Since the period is not equal to one day it must be of several years' duration. My preliminary value of 3.2 years is certainly too short, as will be seen from the velocity curve (Fig. 1). Pending further

[1] Dr. Sanford informs me that his values are based on a few single measures in each case. They agree well with the Yerkes observations.

observations I shall not at this time revise the orbit. However, it is obvious that my conclusions concerning the very large mass of this system are confirmed. As is well known

$$\frac{m_2^3}{(m_1+m_2)^2}\sin^3 i=[3.01642-10]K^3P(1-e^2)^{3/2}\ .$$

K is more than 100 km/sec. and P is longer than 3.2 years. The eccentricity e remains uncertain. But from an inspection of the ob-

TABLE I

RADIAL VELOCITIES OF 27 CANIS MAJORIS

Date	G.C.T.	Observer	Quality	Vel. I	Vel. II
1927 Oct.	3.448	σ,S	f	− 73.3	.....
Oct.	17.460	σ,S	g	− 82.2	+127.7
Nov.	19.338	P,S	g	− 88.3	+168.1
Dec.	8.324	Mt.W	.....	− 93.	.....
Dec.	8.519	Mt.W	.....	− 85.	.....
Dec.	9.306	Mt.W	.....	−100.	.....
Dec.	9.356	B,H,S	g	−104.2	+139.3
Dec.	17.322	P,H,S	g	−106.6	+138.0
Dec.	25.237	σ,S	g	− 88.0	+230.8
1928 Jan.	3.247	σ,S	g	−101.0	+156.4
Jan.	13.302	σ,S	p	− 94.3	.....
Jan.	21.156	σ,S	g	− 85.7	.....
Jan.	21.291	σ,S	g	− 85.6	.....
Jan.	23.251	σ,S	f	− 75.2	.....
Jan.	31.222	B,S	g	− 81.6	.....
Feb.	5.138	σ,S	f	− 74.7	.....
Feb.	10.156	B,H,S	p	− 59.3	.....
Feb.	19.158	B,S	g	− 65.3	+136.6
Feb.	29.100	σ,S	f	− 55.1	.....
Mar.	3.122	P,H,S	g	− 82.9	.....
Mar.	4.117	σ,S	f	− 97.9	.....
Mar.	5.173	P,S	g	−110.2	.....
Mar.	18.072	σ,P,S,	g	−109.2	.....
Mar.	22.062	σ,P,S	p	−117.3	.....
Mar.	28.073	σ,P,S	g	− 97.1	.....
Apr.	2.076	σ,P,S	p	− 90.2	.....
Apr.	11.062	σ,P,S	g	− 74.8	.....

The names of the observers and the quality of the plates are designated as follows: Mt.W = Mount Wilson Observatory; B = S. B. Barrett; H = C. Hujer; P = A. Pogo; S = F. R. Sullivan; σ = O. Struve; g = good; f = fair; p = poor.

served branches we can safely conclude that it can hardly be more than 0.4 or 0.5 and very probably does not exceed 0.3. Indeed, we know from the observations of 1908–9–10 that the maximum is flat and round. The minimum observed in 1927–28 may be steeper, but

it persisted throughout practically the whole season. The descending branch observed in 1926–27 is not steep. Neither does it seem possible to draw a steep ascending branch that would join the minimum with the flat maximum.

If we summarize all available observations we obtain the values given in Table II.

It is now obvious that the value of 1907 cannot lie on the descending branch of the curve. It was this assumption that had originally led to a period of 3.2 years. It now appears that in 1907 the curve was still ascending. This makes it at once evident that

TABLE II

SUMMARY OF RADIAL VELOCITIES OF 27 CANIS MAJORIS

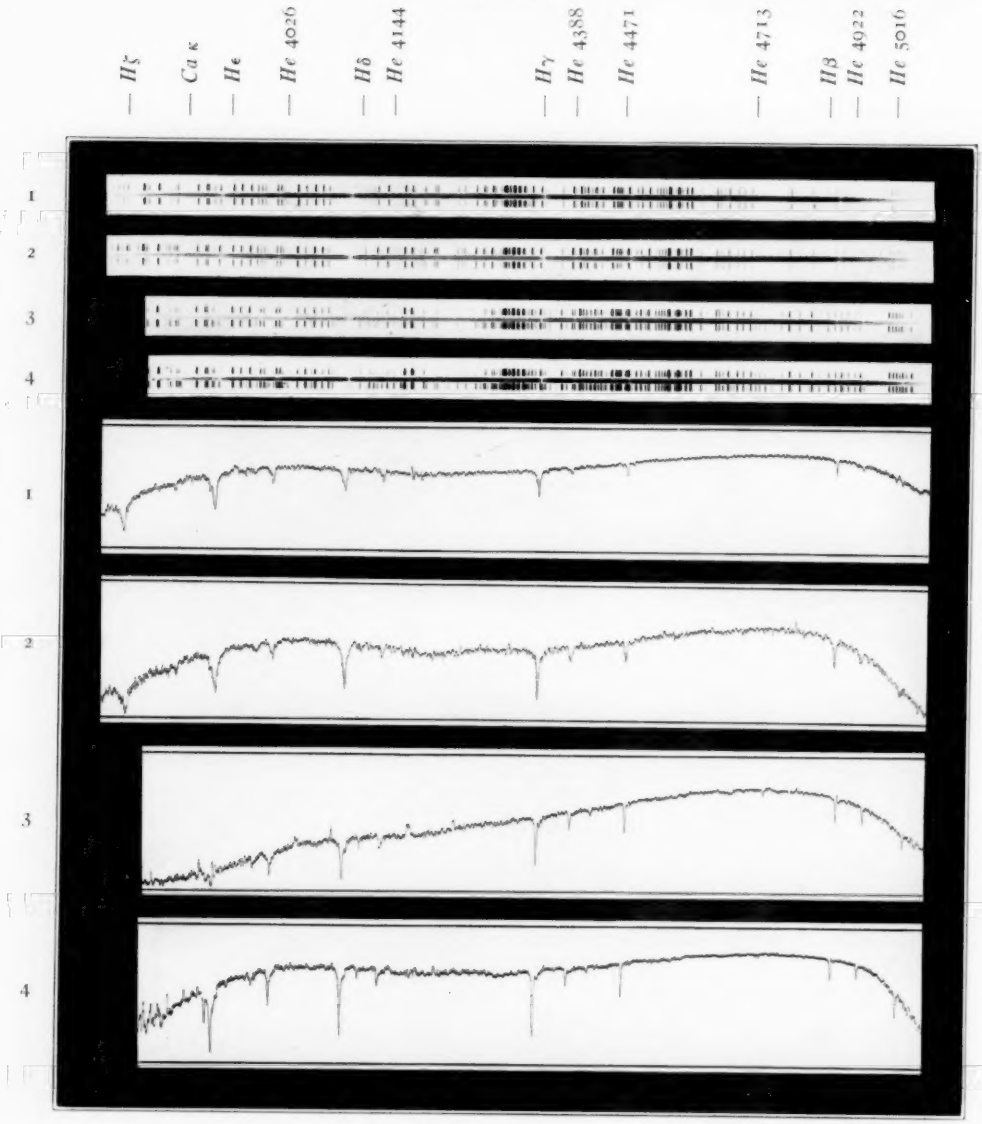
Date	Vel.	Date	Vel.
1907.1	+ 45	1926.0	+ 80
1908.9	+ 90	1926.3	+ 50
1909.2	+100	1926.8	− 30
1909.9	+115	1927.0	− 50
1910.3	+100	1927.3	− 70
1912.9	*	1927.8	− 80
1916.8	+ 20	1928.0	−100
1925.9	+115	1928.3	− 80

* High-positive velocity according to Merrill.

the period is considerably longer than was previously supposed. Maximum occurred in 1910 and again in 1925. The interval is 15 years. Minimum probably took place in about 1915 and again in 1928. The interval is 13 years. Adopting the mean, i.e., 14 years, we conclude that the period is either equal to that value or is a submultiple of it longer than 3.2 years. This leaves the following possibilities: 14 years, 7 years, and 4.7 years. It would be premature to try to settle the exact value now. It is evident, however, that the minimum value of the total mass of this system must exceed 1000 times the mass of the sun.

As I have stated in my previous papers, there is not the slightest *observational* evidence that would allow a doubt as to the binary nature of this star. The spectrum contains bright hydrogen lines, but these are always weak, and cannot be responsible for the displacements observed in the helium lines. It should be noted that the

PLATE III



SPECTROGRAMS OF 27 CANIS MAJORIS WITH MICROPHOTOMETER TRACINGS

1. 1926 Feb. 11, 3^h30^m U.T. meas. vel. +120 km/sec.; reduction to ⊙ −7 km/sec.
2. 1926 Mar. 14, 0:50 U.T. meas. vel. + 85 km/sec.; reduction to ⊙ −17 km/sec.
3. 1928 Jan. 21, 3:45 U.T. meas. vel. −84 km/sec.; reduction to ⊙ −2 km/sec.
4. 1928 Jan. 31, 5:19 U.T. meas. vel. −76 km/sec.; reduction to ⊙ −5 km/sec.

The upper and lower horizontal lines in the tracings represent complete darkness and clear film respectively.

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lines of all the chemical elements represented give the same velocities. The long period cannot be due to pulsations, since that would lead to densities even more unusual than the large value of the mass. Furthermore the absorption lines change their position to an extent much greater than their width, so that the effect cannot be due to unsymmetrical widening.

The most suspicious circumstance is doubtless the presence of the bright hydrogen lines, as will be seen from Plate III. But we know several stars containing emission much more pronounced than that of 27 Canis Majoris that yield perfectly normal velocity curves (for example, H.D. 163181 discussed by Humason and Nicholson).[1] There are a few stars like ϕ Persei and P Cygni in which the absorption lines are directly affected by emission. However, 27 Canis Majoris does not resemble them.

It seems to me that, aside from theoretical reasons, we have no cause at present to doubt the large mass of this star. The only alternative would be to admit that there are agencies (other than orbital motion) at work in the stars that produce variable displacements of lines strikingly similar in all respects to those resulting under the law of gravitation in the simple two-body problem. The acceptance of this alternative would throw doubt upon all our results concerning spectroscopic binaries. While it is true that similar doubts have been entertained by a number of investigators, I believe that there is so much evidence in favor of the double-star hypothesis that the above-mentioned alternative can be neglected entirely. To quote the opinion of Professor J. Hartmann expressed twenty-one years ago:

> Demgenüber kann ich nur bemerken, dass es kaum eine physikalische Tatsache gibt, die so sicher feststeht, wie die, dass δ Orionis ein System von (mindestens) zwei umeinander kreisenden Körpern ist, und dasselbe gilt auch für die weitaus grösste Mehrzahl der sogenannten spektroskopischen Doppelsterne.[2]

The question might be raised whether there exist possible periods other than one day, but shorter than 3 years. A glance at the figure shows that this is not the case. More than 100 observations of this star are now available. The probability that all of them would fit an

[1] *Astrophysical Journal*, **67**, 341, 1928.

[2] *Astronomische Nachrichten*, **175**, 363, 1907.

erroneous period is so minute that it need not be considered. As far as I can see there is no way out of accepting the reality of the long period.

It may be noted here that the observations of 1927–28 again clearly show oscillations of a shorter period and smaller amplitude which are superimposed over the main curve. Figure 1 clearly shows these secondary oscillations. I am inclined to adopt for this shorter period a value of roughly 100 days, the total range being of the order of 50 km/sec. This oscillation greatly resembles the secondary oscillations found by H. Ludendorff in the velocities of 7 ϵ Aurigae.[1]

Whether or not the large mass should be taken literally is open to question. From a purely observational point of view it would violate truth more to disregard the results of observations than to accept the large mass. Nevertheless it must be remembered that the frequency distribution of stellar masses has a comparatively small dispersion, and the probability of finding a star with a mass of more than 1000 $\odot$ is a priori very small. Again it is true that a number of analogous cases are known in astronomy: the large density of the companion of Sirius and the low density of ϵ Aurigae are, statistically, at least as improbable.

If we adopt the *theoretical* point of view, the large mass leads to almost unsurmountable difficulties. It is perhaps not quite certain that a star of this mass will be unstable, although there are indications that stellar masses cannot exceed about 50 times that of the sun.

If we extrapolate Eddington's mass-luminosity curve for $M = 1000\,\odot$, we find that the corresponding bolometric absolute magnitude is about -8. The uncertainty of this value is such that the correction from bolometric to visual magnitude may be neglected. Since the apparent visual magnitude is 4.7, the distance would be $D = 3500$ parsecs. This distance cannot be correct since it would require a strong detached K line of calcium. From my results on interstellar calcium we would expect a residual intensity of about 0^m6 for the detached line. In reality the detached line seems to exist, since I have measured it several times during the last season, but its in-

[1] *Sitzungsberichte der Preussischen Akademie der Wissenschaften, Physikalisch-mathematische Klasse*, **9**, 49, 1924.

tensity is hardly more than $0^m.1$, and the corresponding distance should be less than 200 parsecs. This would lead to an absolute magnitude of about -2 which is more in line with the value of -1 usually adopted for the stars of spectral type B_5. The remaining discrepancy is doubtless due to the fact that B_e stars are intrinsically about 2 magnitudes brighter than ordinary absorption stars.[1]

There can be no doubt that the high absolute magnitude -8 is not correct; consequently we must admit one of two things: either (1) it is not permissible to extrapolate Eddington's mass-luminosity curve, or (2) the large mass may not be real.

There is an unaccountable contradiction between the direct observational results and the demands of the theory. Further accumulation of observational data should help to solve this riddle.

In the accompanying plate (Plate III) I have given enlargements of four of our spectrograms, with their microphotometric tracings. The intensities of the hydrogen lines and of the helium line λ 4472 are especially noteworthy. The bright component at $H\beta$ is visible on some of the reproductions. I am indebted to Dr. A. Pogo for the microphotometer tracings and for the drawing of Figure 1.

YERKES OBSERVATORY
UNIVERSITY OF CHICAGO
July 5, 1928

[1] B. P. Gerasimovič, *Harvard College Observatory Bulletin No. 849*, p. 8, 1927.

SPECTROGRAPHIC STUDY OF THE MULTIPLE SYSTEM Ho 212=13 CETI AB

By ALEXANDER POGO

ABSTRACT

This investigation is based on 100 Yerkes spectrograms of Ho 212=13 Ceti AB (98 one-prism and 2 two-prism plates taken with the Bruce spectrograph attached to the 40-inch refractor) and on the measures of 7 Lick plates and 3 Mount Wilson plates. Aitken's elements of the visual orbit are used.

The *short period*, derived from 21 years of spectrographic observations, is $P=2.08186$ days.

The *orbital elements*, derived from 15 plates secured in 1923, are: $\gamma=+18.4$ km/sec.; $e=0.015\pm0.018$; $K=41.6\pm0.7$ km/sec.; $a \sin i=1{,}180{,}000$ km; mass function, 0.0153 ⊙.

The *orbital elements*, derived from 19 spectrograms taken in 1927–28, are: $\gamma=+13.5$ km/sec.; $e=0.022\pm0.018$; $K=37.1\pm0.8$ km/sec.; $a \sin i=1{,}070{,}000$ km; mass function, 0.0114 ⊙.

The *orbit* is considered *circular;* the *phases* are counted from $T_{min}=1906$ Sept. 30.250 G.M.T. = J.D.2417484.250, corresponding to the passage of the brighter component of the spectroscopic binary through the descending node.

The *positive* sign of the *inclination* of the *visual orbit* is derived from spectrographic and micrometric observations preceding and following the epoch of periastron passage of 1912.15.

The masses of the visual system are estimated hodographically, using Aitken's elements, a parallax $0''.05$, and the range of the γ-values corresponding to the nodes of 1911.98 and 1912.64. The *mass* of the *spectroscopic binary* is found to be 1.22 ⊙, the mass of the *visual companion*, 1.12 ⊙. Total mass of Ho 212: spectro-visual method, 2.34 ⊙, dynamical, 2.39 ⊙.

The *absolute magnitude* of the *spectroscopic binary* is found to be 3.8.

The *amplitude* of the short-period oscillations shows apparent variations, from less than 35 to more than 41 km/sec.; the variations of the *velocity* of the *center of mass* of the spectroscopic binary do not correspond to the visually observed elliptical motion.

Two explanations of these irregularities are offered: (1) if the *spectrum* belongs to the *bright star A only*, there may be masking effects of *physical changes* in the *atmospheres* of its two components; (2) if the *spectrum* belongs to *both components* of the visual system, the fainter star B may be a *close binary B'B''*.

I. RECAPITULATION OF PUBLISHED DATA

S. W. Burnham[1] noted, in 1877, with the $18\frac{1}{2}$-inch Dearborn refractor, that the Flamsteed star 13 Ceti (1900: $\alpha=0^h30^m.1$, $\delta=-4°9'$) has a remote (38″) faint ($12^m.5$) companion. This faint star C is merely a background object, and the measures of the optical pair $\beta490$ formed by the visual system AB and the remote star C can be used for the determination of the proper motion of AB.

[1] *Memoirs of the Royal Astronomical Society*, **44**, 155, 1879. See also the early bibliography in Burnham, *General Catalogue*, **2**, 274, 1906.

In 1886, G. W. Hough[1] found, with the same instrument, that the Flamsteed star was a close binary (0″.3). This visual system, Ho 212 = 13 Ceti AB, has the orbital elements given in Table I, according to R. G. Aitken.[2]

The maximum apparent separation is about 0″.3, the major axis of the apparent ellipse being given as 0″.37, and the distance of the principal star from the center as 0″.12.

In 1907, E. B. Frost[3] announced that the spectrograms secured, by S. B. Barrett and himself, with the Bruce spectrograph attached

TABLE I

TRUE ELEMENTS OF THE VISUAL ORBIT (AITKEN)

Element	Designation	Value
Period	P	6.88 years*
Time of periastron	T	1905.27
Eccentricity	e	0.725
Major semiaxis	a	0″.242
Longitude of periastron	ω	66°.8
Inclination	i	±53°.45
P.A. of nodal point (Angles increasing)	Ω	38°.7

* The only known visual binary having a shorter period, $P = 5.7$ years, is δ Equulei.

to the 40-inch telescope, show a variation of the radial velocity of the brighter visual component, A, with a period of about two days.

P. Fox[4] obtained, by the method of K. Schwarzschild,[5] the elements given in Table II of the two-day orbit, based on 18 spectrograms taken in 1906 and 1907.

J. S. Paraskevopoulos[6] published, in 1920, a paper entitled "The Perturbations of the Orbit of the Spectroscopic Binary 13 Ceti." Table III gives his elements for the orbits of 1906–1907, 1908, 1912–1913, obtained by the method of R. Lehmann-Filhés,[7] followed by a

[1] *Astronomische Nachrichten*, **125**, 3, 1890.

[2] *Publications of the Lick Observatory*, **12**, 6, 1914. See also *Lick Observatory Bulletins*, **3**, 90, 1905; **4**, 107, 1907; **11**, 60, 1923; and **12**, 173, 1927.

[3] *Astrophysical Journal*, **25**, 60, 1907.

[4] *Ibid.*, **27**, 375, 1908.

[5] *Astronomische Nachrichten*, **152**, 65, 1900.

[6] *Astrophysical Journal*, **52**, 110, 1920.

[7] *Astronomische Nachrichten*, **136**, 17, 1894.

least-squares adjustment (6 elements) in the case of the last set of orbital elements. The three orbits are derived from 18, 11, and 10 spectrograms, respectively. Paraskevopoulos also established that the inclination of the visual orbit is positive.

TABLE II

ELEMENTS OF THE SPECTROSCOPIC ORBIT 1906–1907 (FOX)

Element	Designation	(Schwarzschild)
Velocity of system A′A″	γ	+10.5 km/sec.
Period	P	$2^d.0818$
Time of periastron passage	T	J.D.2417484.482
Longitude of periastron	ω	223°.1
Eccentricity	e	0.062
Half-amplitude	K	34.35 km/sec.
Major semiaxis	$a \sin i$	981,460 km

TABLE III

ELEMENTS OF THE ORBITS 1906–1907, 1908, 1912–1913 (PARASKEVOPOULOS)

Element	(Lehmann-Filhés)			Adjusted
	1906–1907	1908	1912–1913	1912–1913
γ	+10.3 km/sec.	+9.0	+16.1	+17.21
P	$2^d.0818$	$2^d.0810$	$2^d.0850$	$2^d.0866 \pm 0^d.0006$
T	J.D.2417484.494	8265.260	9716.581	9716.5706 ± 0.098
ω	222°.7	230°.6	287°.4	$285°.02 \pm 17°.2$
e	0.09	0.07	0.11	0.105 ± 0.038
K	36.4 km/sec.	36.3	33.2	24.18 ± 1.24
$a \sin i$	1,037,262 km	1,036,214	946,040	$975,000 \pm 34,000$

The parallax of 13 Ceti has been determined by different methods; the results are collected in Table IV.

The proper motion of Ho 212 is, according to L. Boss,[1] $\mu_\alpha = +0^s.0272$, $\mu_\delta = -0''.012$, equivalent to $0''.410$ in 92°.8. From the measures of the optical pair $\beta 490 = AB–C$, made between 1877 and 1902, Burnham[2] found, for the visual binary Ho 212, a proper motion of $0''.424$ in 94°.3.

According to the *Henry Draper Catalogue*,[3] the photometric

[1] Ho 212 is Boss 116, in the *Preliminary General Catalogue*.

[2] *General Catalogue of Double Stars*, **2**, 274, 1906.

[3] *Harvard Annals*, **91**, 47, 1918.

magnitude of the system 13 Ceti (H.D. 3196) is 5.24, the color index, 0.56, and the photographic magnitude, 5.80; the spectral type is given as Go. Adams and his associates[1] give 5.7 as the magnitude of the spectroscopic binary, and classify the spectrum as F7 or F8; the absolute magnitude of the spectroscopic binary, calculated from the line-intensities, is given by them as 3.8. According to Aitken,[2] the magnitudes of the visual components are 5.6 and 6.4.

TABLE IV

PARALLAX OF THE SYSTEM Ho 212 = 13 CETI AB

Parallax	Value	Authority
Trigonometric, relative	$0''.048 \pm 0''.010$	Miller, Pitman, and Steele*
Trigonometric, absolute	53	Miller and Pitman†
Dynamical	53	Jackson and Furner‡
Spectroscopic	42	Adams, Joy, Strömberg, and Burwell§
Radioenergetic	($0''.054$)	Brill¶

* *Sproul Observatory Publications*, No. 5, 3, 1920, or *Proceedings of the American Philosophical Society*, **59**, 87, 1920.

† *Astronomical Journal*, **34**, 127, 1922.

‡ *Monthly Notices of the Royal Astronomical Society*, **81**, 22, 1920.

§ *Astrophysical Journal*, **53**, 35, 1921.

¶ *Veröffentlichungen der Universitätssternwarte zu Berlin-Babelsberg*, **7**, 27, 1927.

The mass of the visual system is 2.01 ⊙, according to Miller and Pitman;[3] they used the orbital elements of Aitken and the Sproul absolute parallax, $0''.053$. According to Fox,[4] who used the Sproul relative parallax, $0''.048$, the elements of Aitken give 2.6 ⊙ for the mass of the system Ho 212.

In this paper, the following notations have been adopted:

m' mass of the brighter component A′ of the spectroscopic binary
m'' mass of the fainter component A″ of the spectroscopic binary
M_A mass of the brighter component A of the visual binary
M_B mass of the fainter component B of the visual binary

Greenwich Mean Time (from mean noon to mean noon) is used even after January 1, 1925, for the sake of uniformity.

[1] *Astrophysical Journal*, **53**, 35, 1921.

[2] *Publications of the Lick Observatory*, **12**, 5, 1914.

[3] *Astronomical Journal*, **34**, 130, 1922.

[4] *Annals of the Dearborn Observatory*, **2**, 6, 1925. Apparently a misprint, instead of 2.7 ⊙.

II. SPECTROGRAPHIC MATERIAL, MEASUREMENTS, AND REDUCTIONS

The present investigation of the system Ho 212 = 13 Ceti AB is based on the material given[1] in Table V. The Yerkes spectrograms were taken with one-prism dispersion, except the two early plates of 1906, Nov. 23 and 24, which are two-prism spectrograms. Included in the table are velocities determined at the Lick Observatory[2] from seven spectrograms secured in 1906, 1909, and 1911, and the measurements[3] of three Mount Wilson spectrograms (one prism, 18-inch camera), taken in 1917 and 1918. The plates taken in 1923–1928, and marked IR, were obtained with the Ross quadruplet (aperture, 57 mm; focal length, 599 mm) in the camera of the Bruce spectrograph attached to the Yerkes refractor. "Speedway" plates replaced "Hurricane" in 1924; "Eastman 40" plates were used in 1927–1928, increasing the time of exposure to 3 hours.

The measurements were made on a Gaertner machine, using *Fe* and *Ti* lines of the stellar spectrum, by the method of direct displacements against the spark spectrum of *Fe* and *Ti*. This method was adopted after some of the older plates of 13 Ceti were remeasured on the Hartmann spectrocomparator; the degree of precision is the same; the advantage of the method of direct displacements consists in the possibility of getting acceptable results from weak plates unsuited for the spectrocomparator.

The same set of lines was measured on all plates, and 34 of the better IR plates (1923–1928) were used for the determination of corrections to velocities derived from the individual lines; the average number of lines measured on these 34 selected plates was 11. The same corrections were then applied to the IB spectrograms measured by the method of direct displacements.

The spectrogram IB 1909, used by Paraskevopoulos as the standard plate, and some of the spectrograms which he compared to it on the Hartmann machine, were remeasured on the Gaertner machine, and since no appreciable systematic difference was found, the velocities given in his paper are reprinted without change in Table V.

[1] The table does not include the rejected spectrograms IB 1942 (out of focus), IB 6219 (out of focus), IR 7130 (mid-exposure uncertain), and IR 8680 (changing temperature).

[2] *Publications of the Lick Observatory*, **16**, 6, 1928.

[3] Kindly communicated by A. H. Joy.

TABLE V

SPECTROGRAPHIC MATERIAL

No.	Plate	Midexposure G.M.T.	Secured By	Wt.	Phase days	Velocity km/sec.	O.−C. km/sec.
1...	.....	1906 Sept. 21.86	Lick Obs.	.....	2.02	−39.0	(−13.2)
2...	IB 872	Oct. 1.788	B, S	1	1.538	+15.5	+ 2.9
3...	912	Nov. 9.589	B, S	1	0.784	+40.8	+ 4.8
4...	IIB 87	Nov. 23.544	F, B, S	0.7	0.166	−22.7	− 0.7
5...	90	Nov. 24.554	F, Fx, S	1	1.176	+39.0	− 4.5
6...	IB 917	Nov. 27.514	F, B, S	0.7	2.054	−28.2	− 1.8
7...	919	Dec. 1.542	F, Fx, S	0.7	1.918	−23.2	− 1.1
8...	921	Dec. 3.610	F, Fx, S	1	1.904	−18.0	+ 3.4
9...	951	1907 Jan. 25.531	B, S	1	0.697	+33.2	+ 4.7
10...	1164	Sept. 13.872	F, S	0.7	0.951	+43.3	− 2.9
11...	1170	Sept. 21.787	F, B, S	1	0.539	+20.6	+ 7.6
12...	1215	Oct. 20.696	F, S	1	0.302	−12.0	− 0.6
13...	1244	Nov. 23.592	L, S	0.7	0.888	+44.5	+ 0.8
14...	1249	Nov. 25.601	L, S	0.7	0.815	+39.8	+ 0.5
15...	1255	Nov. 27.610	Fx, B	0.7	0.742	+36.2	+ 2.6
16...	1259	Nov. 30.604	Fx, S	0.7	1.654	+ 2.0	+ 2.9
17...	1264	Dec. 4.571	Fx, S	1	1.457	+21.2	− 1.1
18...	1273	Dec. 6.504	F, Fx	1	1.309	+33.9	− 2.3
19...	1277	Dec. 6.701	Fx, S	1	1.506	+14.0	− 3.1
20...	1731	1908 Sept. 8.825	B, L, S	0.7	1.743	− 8.4	+ 2.9
21...	1808	Oct. 30.699	B, S	1	1.571	+17.2	+10.3
22...	1833	Nov. 8.608	F	0.7	0.070	−29.9	− 1.7
23...	1852	Nov. 13.614	B, S	0.7	0.912	+39.7	− 2.5
24...	1859	Nov. 16.500	L	1	1.717	− 0.1	+ 8.6
25...	1865	Nov. 16.743	L, S	0.7	1.960	−25.2	+ 1.3
26...	1871	Nov. 21.538	F, S	0.7	0.509	+ 8.1	+ 1.4
27...	1884	Dec. 4.708	B, S	0.7	1.188	+40.2	− 1.2
28...	1893	Dec. 7.542	F, L, S	1	1.940	−23.4	+ 2.3
29...	1899	Dec. 11.562	F, S	1	1.796	−16.8	− 0.7
30...	1909	Dec. 21.531	L	1	1.356	+34.2	+ 4.7
31...	1936	Dec. 28.499	F, B, L, S	1	2.078	−28.9	+ 0.1
32...	.....	1909 July 23.99	Lick Obs.	.....	1.39	+24.9	.....
33...	IB 2568	1910 Nov. 28.525	F, B, S	0.3	0.518	+19.7	.....
34...	2575	Dec. 12.513	F, B, A	1	2.015	−13.1	.....
35...	.....	1911 Aug. 6.99	Lick Obs.	.....	0.08	−45.3	− 5.4
36...	.....	Aug. 29.99	Lick Obs.	.....	0.18	−39.6	− 4.1
37...	.....	Sept. 11.92	Lick Obs.	.....	0.62	+18.6	+10.4
38...	.....	Oct. 27.72	Lick Obs.	.....	0.62	+20.2	+12.0
39...	.....	Oct. 28.80	Lick Obs.	.....	1.70	−22.6	− 4.2
40...	IB 3147	1912 Nov. 8.681	L, S	0.7	1.759	+ 0.4	+ 2.8
41...	3153	Nov. 18.569	L, S	0.7	1.238	+38.6	− 7.0
42...	3174	Nov. 29.535	L, S	1	1.794	− 7.7	− 2.4
43...	3184	Dec. 6.522	L, S	0.7	0.454	+ 9.3	− 0.8
44...	3200	Dec. 23.507	L, S	0.7	0.784	+41.8	+ 0.2
45...	3213	Dec. 25.511	L, S	1	0.706	+36.5	+ 1.2
46...	3215	Dec. 27.499	L, S	1	0.612	+21.3	− 5.1
47...	3229	1913 Jan. 8.506	L, S	1	0.128	−16.0	− 1.1
48...	3235	Jan. 13.510	L, S	1	0.968	+51.4	+ 0.8
49...	3243	Jan. 20.538	L, S	0.7	1.751	+ 9.4	+11.1
50...	4739	1917 Jan. 3.510	B, M	1	0.912	+57.7	+ 1.9
51...	4755	Jan. 15.532	B, M	1	0.443	+12.7	+ 5.4
52...	4773	Jan. 22.520	B, M	1	1.185	+54.2	− 0.9

TABLE V—*Continued*

No.	Plate	Midexposure G.M.T.	Secured By	Wt.	Phase days	Velocity km/sec.	O.−C. km/sec.
53...	IB 4787	1917 Jan. 29.525	B, M	0.7	1.946	−29.9	− 8.4
54...	4799	Feb. 5.531	B, M	1	0.623	+25.9	− 3.9
55...	γ 6179	Sept. 3.975	Mt. Wilson		0.799	+38.3	.....
56...	γ 6466	Dec. 26.651	Mt. Wilson		2.055	−19.1	.....
57...	γ 7178	1918 Sept. 15.889	Mt. Wilson		0.897	+41.1	.....
58...	IB 5645	1919 Dec. 15.508	B, Pr	1	0.588	+19.8	− 3.3
59...	5649	Dec. 19.485	B, Pr	1	0.401	+14.2	+10.5
60...	5655	Dec. 26.493	B, Bk	0.7	1.164	+44.9	− 3.7
61...	5661	1920 Jan. 2.517	B, Pr	0.7	1.942	−20.3	− 4.4
62...	6192	1921 July 8.909	Pr, S	0.3	1.560	− 1.7	.....
63...	IR 7036	1923 Aug. 9.905	σ, S	0.3	1.595	+20.5	+ 6.3
64...	7051	Aug. 18.892	σ, S	0.7	0.173	−17.6	+ 0.1
65...	7067	Aug. 21.887	σ, S	0.3	1.086	+61.1	+ 1.5
66...	7093	Sept. 8.817	σ, S	0.7	0.279	−10.8	− 1.6
67...	7099	Sept. 10.774	σ, S	0.3	0.154	−18.6	+ 0.2
68...	7104	Sept. 11.781	σ, S	1	1.161	+57.8	+ 0.5
69...	7109	Sept. 15.745	σ, S	0.7	0.962	+60.2	+ 1.4
70...	7117	Sept. 18.758	B, S	0.7	1.893	−19.9	− 3.3
71...	7124	Sept. 22.762	σ, S	0.7	1.733	+ 0.6	+ 2.8
72...	7151	Oct. 6.759	σ, S	0.3	1.157	+60.8	+ 3.4
73...	7158	Oct. 7.712	B, S	0.7	0.028	−20.3	+ 2.7
74...	7164	Oct. 14.648	B, S	0.7	0.718	+36.8	− 5.0
75...	7171	Oct. 20.688	σ, S	1	0.513	+19.5	+ 2.0
76...	7179	Oct. 21.658	B, S	1	1.483	+26.7	− 1.5
77...	7188	Oct. 22.665	σ, S	1	0.408	+ 0.9	− 3.7
78...	7541	1924 Oct. 19.672	σ, S	1	1.172	+56.0	.....
79...	7560	Oct. 25.654	σ, S	0.3	0.908	+43.0	.....
80...	7875	1925 Sept. 2.828	σ, E, S	1	0.803	+36.8	+ 3.4
81...	7898	Sept. 23.782	B, σ, S	0.7	0.938	+34.8	− 5.5
82...	7904	Sept. 27.735	σ, S	0.7	0.727	+25.2	− 2.2
83...	7908	Oct. 4.784	B, σ, S	0.7	1.531	+13.1	+ 2.9
84...	7949	Nov. 1.715	σ, S	0.3	0.316	−12.1	+ 1.2
85...	8000	1926 Jan. 6.507	B	0.7	1.570	+24.5	.....
86...	8211	Oct. 7.669	σ, S	0.3	0.927	+41.9	− 8.7
87...	8219	Oct. 14.738	σ, Mg, S	1	1.750	− 3.1	+ 5.5
88...	8229	Oct. 25.673	σ, Mg, S	0.7	0.194	−27.5	− 7.2
89...	8237	Oct. 30.662	Mg, S	1	1.020	+53.6	+ 0.7
90...	8286	Dec. 30.503	B	1	1.487	+22.6	+ 0.7
91...	8295	1927 Jan. 6.506	σ	1	0.162	−25.0	− 2.7
92...	8586	Oct. 20.726	B, P, S	0.7	0.085	−26.1	− 3.7
93...	8591	Oct. 21.725	σ, P, S	0.7	1.084	+49.3	− 1.0
94...	8598	Oct. 25.622	B, P, S	0.7	0.817	+46.2	+ 3.8
95...	8603	Oct. 26.692	P, S	0.7	1.887	−15.9	+ 1.5
96...	8610	Nov. 3.601	B, P, S	1	1.469	+26.2	+ 2.5
97...	8614	Nov. 4.661	P, S	0.3	0.447	+ 1.2	− 4.1
98...	8617	Nov. 12.569	B, P, S	0.7	0.028	−25.2	− 1.7
99...	8620	Nov. 18.635	B, P, S	0.3	1.930	−23.1	− 3.3
100...	8626	Dec. 8.551	B, P, S	1	1.027	+50.6	0
101...	8642	Dec. 19.594	B, H, S	0.7	1.661	+ 4.1	+ 1.6
102...	8647	Dec. 20.559	B, P, S	1	0.544	+13.3	− 2.8
103...	8665	1928 Jan. 2.515	σ, P, S	0.7	1.009	+46.3	− 4.1
104...	8676	Jan. 3.554	B, P, S	0.7	2.048	−23.8	− 0.4
105...	8689	Jan. 11.554	B, P, S	0.7	1.720	− 0.7	+ 2.9

TABLE V—*Continued*

No.	Plate	Midexposure G.M.T.	Secured By	Wt.	Phase days	Velocity km/sec.	O.−C. km/sec.
106...	IR 8695	1928 Jan. 17.517	B, P	0.7	1.438	+28.3	+ 1.3
107...	8716	Jan. 22.512	σ, P	0.3	0.187	−16.2	+ 1.7
108...	8732	Jan. 26.517	σ, P, H	0.3	0.029	−19.5	+ 4.0
109...	8733	Jan. 30.524	B, P, S	0.7	1.954	−20.6	+ 0.3
110...	8744	Feb. 3.522	B, P, H	0.7	1.788	+ 1.4	+11.3

NOTE.—The names of the observers are abbreviated as follows: A=E. C. Arbogast, B=S. B. Barrett, Bk=Miss D. W. Block, E=C. T. Elvey, Fx=P. Fox, F=E. B. Frost, H=C. Hujer, L=O. J. Lee, M=G. S. Monk, Mg=W. W. Morgan, Pr=J. S. Paraskevopoulos, P=A. Pogo, σ=O. Struve, S=F. R. Sullivan.

III. SPECTRUM OF 13 CETI

The visual companion B is separated, at apastron, by about 0".3 from the spectroscopic binary A; this is about one-tenth of the minimum distance for visual binaries which can be brought separately on the slit of the Bruce spectrograph attached to the 40-inch refractor.

If the difference in photographic brightness of the two visual components were at least a full magnitude,[1] and the exposures short, we could be sure that the spectrum of the brighter component only would make its impression on the plates. We shall see that there are reasons to believe that the difference in brightness of the components of Ho 212 is insufficient to exclude completely the spectrum of B from our spectrograms of A.

The fainter component A″ of the spectroscopic binary appears to have no influence on the recorded spectrum of the principal component A′. There are, however, plates corresponding to the passage of the spectroscopic binary through the nodes of the two-day orbit, and showing an abnormal width of the otherwise very sharp iron lines at λ 4404 and λ 4415.

The star A′ producing the measurable spectrum on our plates does not seem, therefore, to be the only component of the system Ho 212 able to leave its record on spectrograms of long exposure corresponding to certain positions of the different members of the system in their respective orbits. Variations in the amplitude of ve-

[1] See the conclusions of O. Struve, in his study of the spectrum of the close visual binary 9 Argus, *Astrophysical Journal*, **58**, 148, 1923.

locity-curves, and irregularities in the variation of the velocity of the center of mass of the spectroscopic binary, will be discussed later.

Figure 1 reproduces the record of the intensity-curve obtained with the self-registering microphotometer[1] from a good IR spectrogram. The distance between $H\delta$ and $H\beta$ is 26.32 mm on the plate, and 416 mm on the original record. The lines of *Fe* and *Ti* measured on our spectrograms are marked on the record and given in Table VI; the last column of the table gives the corrections to velocities,

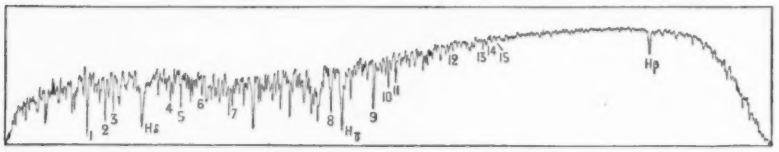


FIG. 1.—Intensity-curve of the spectrogram IR 7179 of 13 Ceti

TABLE VI

MEASURED LINES AND CORRECTIONS TO VELOCITIES

STAR LINE	SPARK		CORRECTION (KM/SEC.)
	Element	Wave-Length (I.A.)	
1	*Fe*	4045.818	.....
2	*Fe*	4063.621	−1.2
3	*Fe*	4071.758	.....
4	*Fe*	4132.062	−1.9
5	*Fe*	4143.682	+4.4
6	*Ti*	4163.647	+5.2
7	*Fe*	4202.033	−2.5
8	*Fe*	4325.762	.....
9	*Fe*	4383.550	+3.4
10	*Fe*	4404.719	−6.0
11	*Fe*	4415.191	−2.2
12	*Ti*	4501.269	.....
13	*Ti–Fe*	4549.532	−6.4
14	*Ti*	4563.757	+2.1
15	*Ti*	4571.970	+5.5

as derived from the individual lines of the selected 34 plates mentioned in the preceding section; corrections smaller than 1 km/sec. were omitted.

[1] Designed by C. T. Elvey; constructed by C. Ridel; *Ag-Bi* thermopile by W. W. Coblentz; galvanometer by Leeds and Northrup.

IV. PERIOD OF THE SPECTROSCOPIC BINARY A′A″

A preliminary velocity-curve based on the spectrograms secured in October and November, 1927, indicated that a mean period of 2.08186 days would satisfactorily connect the minimum velocity of 1927 Oct. 20.64 with the minimum velocity of 1906 Sept. 30.25. There were 3694 complete revolutions of the system A′A″ between these two passages of A′ through the descending node of its two-day orbit.

The mean period $P = 2^{d}08186$ satisfies all the available spectrographic observations, as is shown by the velocity-curves of Figures 2, 3, and 4. The minimum radial velocity, i.e., the passage of A′ through the descending node of the spectroscopic orbit, corresponding to $T_0 =$ 1906 Sept. 30.250 = J.D. 2417484.250 G.M.T. was taken as origin of phases.

The period derived by P. Fox from the spectrographic observations of 1906–1907 was $P = 2^{d}0818$; now, after twenty years, we can improve the fourth decimal place.

If there are changes in the mean period $P = 2^{d}08186$, depending on the position of the spectroscopic binary in its long-period orbit, they cannot be deduced with any degree of certainty from the available material. As a matter of fact, the following less-refined deduction from the observed and computed minima of radial velocities leads to no acceptable results.

It should theoretically be possible to find the spectro-visual parallax of a spectrographically observable visual binary, by postulating the constancy of the short period, and by computing the differences between the epochs of the "expected" and the observed minima (or maxima) of the velocity-curves corresponding to different positions of the spectroscopic binary in its long-period orbit. The time spent by light in reaching the plane of the sky passing through the center of mass of the visual system would give the linear dimensions of the absolute orbit of the center of mass of the spectroscopic binary; if we know the approximate distribution of masses in the visual system, we would have the linear dimensions of the true relative orbit of the visual companion, and since we know the apparent angular dimensions of the true orbit of B around A, we would have the spectro-visual parallax of the system.

The heliocentric light-equation of 13 Ceti gives a correction of +8 minutes for observations made in the end of September, and of −5 minutes for the end of January. If we assume an equal distribution of masses in the visual system, $M_A = M_B$, and a parallax $\pi = 0''.05$, the major axis of the true orbit of the spectroscopic binary A around the center of mass of the visual system AB would be about 5 astronomical units; the corresponding astrocentric light-equation shows that the range of the light-time is more than 30 minutes between periastron and apastron, and that near the apastron the correction exceeds −25 minutes during two years (flat minimum of the astrocentric light-curve).

Unfortunately, the residuals obtained by comparing the phases of observed minima corresponding to the different positions of A in the long-period orbit with the adopted phase zero indicate no simple periodic oscillations. Although the astrocentric light-time can produce a shift of a minimum of the order of 0.02 days, i.e., of 1 per cent of the short period, the effect is masked by apparently erratic shifts of the minima parallel to the axis of phases.

By shifting some of the curves of Figure 2 slightly to the right or to the left, some of the most conspicuous residuals of Table V can be considerably reduced. For the sake of uniformity, however, all the curves of Figure 2 were computed in such a way as to satisfy the formula

$$T_{min} = \text{J.D.}2417484.250\ \text{G.M.T.} + 2.08186N\ ,$$

N being an integer.

For reasons given in another section, the curves of Figure 2 correspond to circular motion. Table XI gives the values of K and γ used in the computation of the sine-curves of Figure 2, and of the residuals of Table V. The residuals of Table V could be improved not only by shifting the curves slightly in time, but also in velocity, or even by slightly changing their amplitudes. These refinements did not appear to be necessary or even useful.

The following isolated observations, included in Tables V and XI, are not represented in Figure 2:

1. Nos. 33 and 34 (1910). The observed velocities fit perfectly the curve of 1926.02. By adding the reduced value of K, 35 km/sec.,

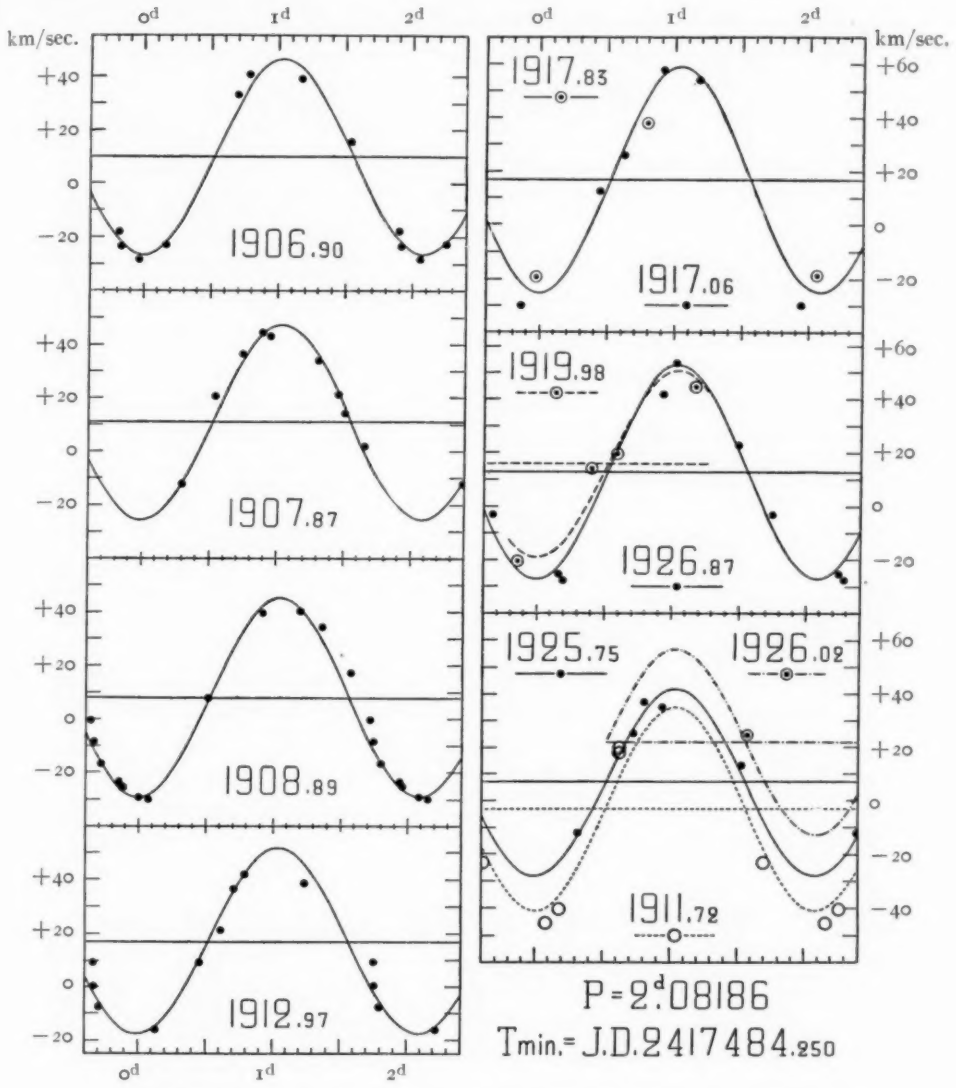


FIG. 2.—Radial-velocity curves of 13 Ceti A′. Phase 0d corresponds to T_0 = J.D. 2417484.250 = 1906 Sept. 30.250 G.M.T.

to the velocity, − 13 km/sec., derived from the spectrogram No. 34 (weight: unity, phase: near minimum), we obtain +22 km/sec., a conservative estimate of the γ-value for 1910.93.

2. Nos. 78 and 79 (1924). By subtracting the maximum value of K, 42 km/sec., from the velocity, +56 km/sec., indicated by the spectrogram No. 78 (weight: unity, phase: near maximum), we find +14 km/sec., a conservatively estimated value of γ for 1924.81.

The isolated observations Nos. 1, 32, and 62 are not included in Table XI, and are not represented in Figure 2. The first Lick spectrogram, corresponding to phase minimum, shows a remarkably large negative velocity; if included in the Yerkes series of 1906.90, it would corroborate the impression, mentioned in section XI, that the γ-value was smaller in 1906.90 than in 1907.87.

V. SHORT-PERIOD ORBIT, BASED ON OBSERVATIONS OF 1923

As phase zero we took the "expected" minimum preceding the first observation of 1923; it falls on T_{2957} = 1923 Aug. 8.310 G.M.T. = J.D. 2423640.310, and corresponds to the 2957th passage of A′ through the descending node since T_0 = 1906 Sept. 30.250.

The preliminary elements of the orbit of 1923.72 were read from the freehand velocity-curve, by applying the principles, not the construction given by the writer in his article[1] on the hodographic method of K. Laves.[2] To decide whether the periastron point was near the maximum or near the minimum of the almost sinusoidal velocity-curve, the rule: "periastron point and γ-axis are on opposite sides of the S-axis" was applied; thus a preliminary value $\omega = 0^\circ$ was found for the longitude of the periastron. The corresponding eccentricity was therefore given by the ratio of the distance between the γ-axis and the S-axis to the half-amplitude K; the preliminary value of the eccentricity thus read off the velocity-curve was $e = 0.04$.

The preliminary elements, collected in Table VII, were adjusted by the method of least-squares (15 observations, 5 unknowns). Weights, on the scale 1, 0.7, 0.3, were attributed to the individual spectrograms, according to the quality and number of measured stellar lines, the quality of the comparison spectra, and the scattering

[1] *Astrophysical Journal*, **67**, 262, 1928.

[2] *Ibid.*, **26**, 164, 1907.

of the individual velocities of each plate. The tables of F. Schlesinger[1] were used for the computation of the coefficients of the normal

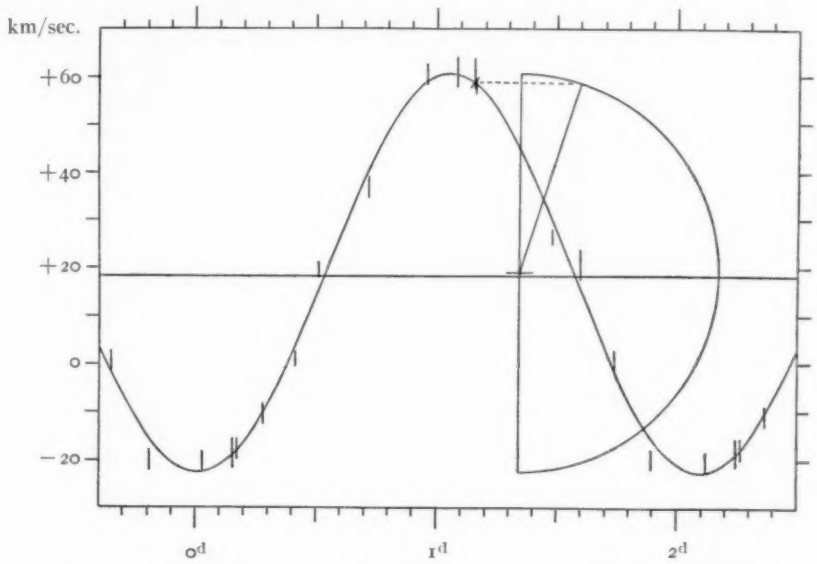


FIG. 3.—Radial-velocity curve of 13 Ceti A′ for 1923.72. Phase 0d corresponds to T_{2957} = J.D. 2423640.310 G.M.T.

TABLE VII

ELEMENTS OF THE SPECTROSCOPIC ORBIT 1923

Element	Preliminary	Correction	Adjusted	Probable Error
γ	+18.4 km/sec.	−0.04	+18.4 km/sec.	
P	$2^d.08186$	(adopted)	$2^d.08186$	
T	J.D.2423641.351	$+0^d.101$	2423641.452	$\pm 0^d.206$
ω	0°	+18°.1	18°.1	±35°.3
e	0.04	−0.025	0.015	±0.018
K	40.0 km/sec.	+1.59	41.6 km/sec.	±0.7 km/sec.
$a \sin i$			1,180,000 km	
$\frac{(m'' \sin i)^3}{(m'+m'')^2}$			0.0153 ⊙	

equations. For the solution of the normal equations, the method of M. H. Doolittle[2] was used. The sum of the weighted squares of the

[1] *Publications of the Allegheny Observatory*, **1**, 33, 1908.

[2] *U.S. Coast and Geodetic Survey Report*, 1878, App. 8. See also O. M. Leland, *Practical Least Squares*, New York, 1921.

residuals was reduced from 80.70 to 63.90. The probable error of a single observed velocity of weight unity was found to be 1.71 km/sec. The adjusted elements and their probable errors are given in Table VII.

Figure 3 represents the velocity-curve computed from the adjusted elements. The observed velocities are indicated by vertical lines, equal, on the scale of radial velocities, to twice their respective probable errors. The length of the major semiaxis of the indeterminately inclined two-day orbit and the mass-function of the spectroscopic binary A′A″ were obtained by the hodographic method, using the adjusted elements.

The residuals given in the last column of Table V were computed for a circular orbit (see sec. VIII of this paper).

For reasons indicated in section XI, the velocity of the center of mass of the spectroscopic binary A appeared to be too high. To eliminate the improbable possibility of an instrumental error of the

TABLE VIII

CONTROL OBSERVATIONS OF 34 *o* CEPHEI

(1900: $\alpha = 23^h14^m5$, $\delta = +67°34'$)

Observatory	Date	Velocity
Lick	1923 Sept. 10	−18.4 km/sec.
Lick	Sept. 18	−16.5
Lick	1903–1923	−17.8
Yerkes	1923 Sept. 8	−14.5
Yerkes	Sept. 23	−14.3

order of 10 km/sec., two good spectrograms of the 4.9-magnitude G5-type star 34 *o* Cephei (brighter component), secured in September, 1923, under the same instrumental conditions as the six spectrograms of 13 Ceti taken in September, 1923, were measured on the Gaertner machine, by the method of direct displacements, using the *Fe* and *Ti* lines given in Table VI. In Table VIII we compare these measurements of the two Yerkes spectrograms of 34 *o* Cephei with Lick observations[1] of the same epoch; the velocities are of the same order.

[1] *Publications of the Lick Observatory*, **16**, 339, 1928.

The large value of the radial velocity of the center of mass of the spectroscopic binary A in the system of 13 Ceti, derived from the observations of 1923.72, cannot, therefore, be ascribed to instrumental errors. The variations of γ will be discussed in section XI.

VI. SHORT-PERIOD ORBIT, BASED ON OBSERVATIONS OF 1927–1928

As phase zero we took T_{3694} = 1927 Oct. 20.641 G.M.T. = J.D. 2425174.641, the computed epoch of minimum preceding the first observation of the season, and corresponding to the 3694th passage of the bright component A′ through the descending node, counted from the adopted initial epoch of minimum, T_0 = 1906 Sept. 30.250 G.M.T.

As in the case of the orbit of 1923.72, the almost sinusoidal free-hand velocity-curve intercepted on the S-axis practically equal segments, so that the criteria of a shorter intercept on the S-axis, of a steeper periastron-branch, or of a sharper periastron-arc, could not be applied in order to decide whether the periastron point should be taken near the maximum or near the minimum of the velocity-curve. Since the γ-axis, as indicated by the observations of 1927.95, was above the mean axis, the preliminary value assigned to the longitude of periastron was $\omega = 180°$, corresponding to the periastron point coinciding with the minimum of the velocity-curve.

The ratio of the distance between the mean axis and the axis of center of mass to the half-amplitude of oscillations gave the preliminary value of the eccentricity of the orbit, $e = 0.03$.

The preliminary values of the elements, and the values adjusted by the method of least-squares (19 observations, 5 unknowns), as well as their probable errors, are given in Table IX. The sum of the weighted squares of the residuals, derived from the preliminary ephemeris, was 117.95; the ephemeris computed with the adjusted elements reduced this sum to 99.37. The probable error of an observation of unit weight was found to be 1.79 km/sec. The values of the functions of mean distance and of mass were computed hodographically, using the adjusted elements.

The velocity-curve computed from the adjusted elements of the orbit of 1927.95 is represented in Figure 4; the observed velocities

and their respective probable errors are represented by vertical lines, as in the case of the orbit of 1923.72.

The residuals given in the last column of Table V were computed for a circular orbit (see sec. VIII of this paper).

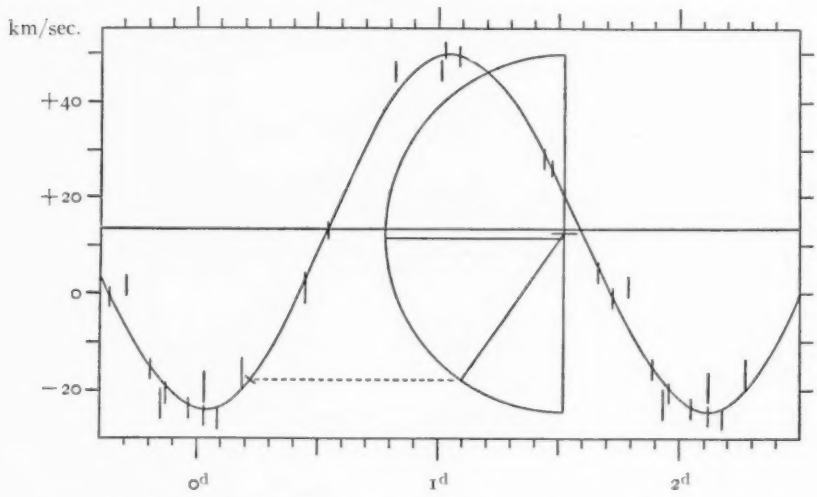


FIG. 4.—Radial-velocity curve of 13 Ceti A′ for 1927.95. Phase 0d corresponds to T_{3694} = J.D. 2425174.641 G.M.T.

TABLE IX

ELEMENTS OF THE SPECTROSCOPIC ORBIT 1927–1928

Element	Preliminary	Correction	Adjusted	Probable Error
γ	+13.7 km/sec.	−0.2	+13.5 km/sec.	
P	$2^d.08186$	(adopted)	$2^d.08186$	
T	J.D.2425174.641	$+0^d.216$	J.D.2425174.857	$\pm 0^d.168$
ω	180°	+35°.5	215°.5	±92°.4
e	0.03	−0.008	0.022	±0.018
K	37.5 km/sec.	−0.4	37.1 km/sec.	±0.8 km/sec.
$a \sin i$			1,070,000 km	
$\frac{(m'' \sin i)^3}{(m'+m'')^2}$			0.0114 ⊙	

VII. LINE OF APSIDES OF THE SPECTROSCOPIC ORBIT

The very large probable errors of the adjusted values of the longitude of periastron of the two-day orbit, as derived from the observations of 1923.72 and 1927.95, indicate the impossibility of

deriving a reliable value of the longitude of periastron of this practically circular orbit.

According to the observations of 1923.72, the periastron is in the neighborhood of the ascending node; according to the observations of 1927.95, it is in the neighborhood of the descending node, although the uncertainty of the determination is such that the angle between the line of nodes and the line of apsides can be considered as indeterminate.

We have the case of a circular orbit, not the case of a motion of the line of apsides.

There is another reason why it would be futile to interpret these discordant results as a motion of the line of apsides. P. Slavenas[1] has shown that the ratio of the short period P to the period U of the motion of the line of apsides of the spectroscopic orbit can be expressed as follows, P' designating the period of the visual binary, and k the ratio of the mass m' of the bright spectroscopic component to the total mass M_A+M_B of the system:

$$\frac{P}{U}=\frac{3}{4}k\left(\frac{P}{P'}\right)^2+\frac{225}{32}k^2\left(\frac{P}{P'}\right)^3+\ldots\ldots.$$

The terms depending on the eccentricities of the two orbits, and on their relative inclination, can be safely omitted in our case. Whatever the probable distribution of masses in the system Ho 212 may be, the first term of the series, depending on the square of the ratio of two days to seven years, shows that the period U of the motion of the line of apsides of the spectroscopic orbit is of the order of thousands of years.

VIII. ECCENTRICITY OF THE SPECTROSCOPIC ORBIT

The spectrographic observations of 1923.72 and 1927.95 indicate that the eccentricity of the two-day orbit is very small, $e=0.015\pm 0.018$ or 0.022 ± 0.018. The order of the probable errors of these very small values of the eccentricity justifies the simplifying assumption that the orbit is circular. The discordant values of the longitude of periastron become meaningless.

[1] *Transactions of the Yale University Observatory*, **6**, 41, 1927, and *Proceedings of the National Academy of Sciences*, **13**, 834, 1927.

The velocity-curves of Figure 2 and the residuals O. − C. of Table V were computed on the assumption that $e = 0$; phases were counted from a passage of A′ through the descending node; the values of K and γ adopted for the computation of the curves of Figure 2 and of the residuals of Table V are given in Table XI.

The circular orbit represents the observations of 1923.72 and of 1927.95 quite satisfactorily. The sine-curves reproduced in Figure 2

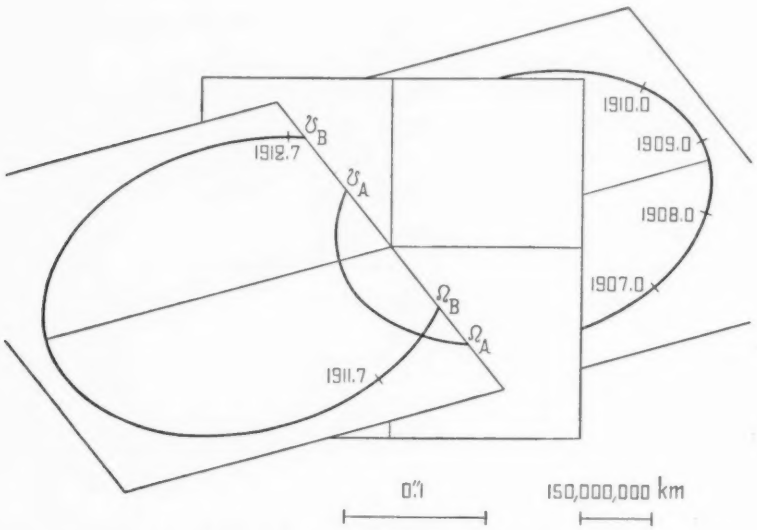


FIG. 5.—True absolute orbits of 13 Ceti A and 13 Ceti B. The plane of the orbits is represented after a rotation through 53° around the line of nodes. In the central square (plane of the sky) north is below. With the data adopted in this paper, 1 astronomical unit would be represented by about 11 mm.

would fit the observations more closely, if the selective influence of the limited number of the available observations could be eliminated, and the astrocentric and heliocentric light-equations taken into account.

IX. SIGN OF THE INCLINATION OF THE VISUAL ORBIT

The inclination $i = \pm 53°.45$ of the relative orbit of the visual companion B (around the principal star A), or of its absolute orbit (around the center of mass of the visual system), is—by definition—positive, if the companion B, passing through the node following (in

the first or second quadrant) of the apparent ellipse, has a larger radial velocity of recession or a smaller velocity of approach than the center of mass of the visual system.

The negative value of the velocity of the center of mass of the spectroscopic binary, derived from the Lick spectrograms of 1911.72, shows that they correspond to an approach of A to the descending node (epoch of passage, 1911.98) of its orbit around the center of mass of the visual system.

The large velocity of recession of the spectroscopic system, indicated by the Yerkes spectrograms of 1912.97, shows that they correspond to a recession of A from the ascending node (epoch of passage, 1912.64) of its seven-year orbit.

TABLE X

EPOCHS OF APSIDES AND NODES
(Derived from Aitken's Elements)

υ_A and Ω_B	Periastron	Ω_A and υ_B	Apastron
1905.10	1905.27	1905.76	1908.71
1911.98	12.15	12.64	15.59
18.86	19.03	19.52	22.47
25.74	25.91	26.40	29.35
32.62	32.79	33.28	36.23

Aitken's micrometric observations of the visual companion B, in the first quadrant, in 1911.78, and in the third quadrant, in 1912.65, were therefore made shortly before the epoch of passage of B through the ascending node (1911.98), and immediately after the epoch of passage of B through the descending node (1912.64), respectively.

The node in the first quadrant being the ascending node of the apparent ellipse, the inclination of the visual orbit is positive, $i = +53°.45$.

This result, derived from two sets of spectrograms secured around the epochs of the passage of A through the nodes, and corroborated by micrometric observations made before and after the epoch of periastron passage, is not affected by the irregularities in the change of the values of γ, discussed in section XI.

The sign of the inclination of the visual orbit should not be

derived from values of γ which differ but little, and belong to epochs separated by several years. Blend-effects or the presence of a fourth body in the visual system AB may then lead to wrong conclusions, as can be easily seen (Fig. 7) from a comparison of the values of γ for 1923.72 and 1927.95, or for 1906.90, 1907.87, and 1917.06, which would suggest an ascending apastron-branch, and therefore a descending periastron-branch of the long-period velocity-curve of A, thus apparently reversing the sign of the inclination of the visual orbit, established by the observations of 1911.72 and 1912.97, and corroborated by the observations of 1925.75 and 1926.02.

The positive sign of the inclination of the visual orbit, derived by Paraskevopoulos from the comparison of the γ-values for 1906–1907, 1908, and 1912–1913, is correct, but the method used by him could easily lead to the opposite result.

X. SPECTRO-VISUAL ESTIMATION OF MASSES

The dynamical method of finding the total mass of a visual binary whose orbital elements and parallax are known, based on the harmonic law of Kepler,

$$\frac{M_A+M_B}{\odot}=\frac{1}{P^2}\cdot\frac{a^3}{\pi^3},$$

gives, with the orbital elements of Aitken, $a=0''.242$, $P=6.88$ years, and an adopted parallax, $\pi=0''.05$,

$$M_A+M_B=2.39\ \odot$$

for the total mass of Ho 212.

Approximate values of the separate masses M_A and M_B can be derived in the following way from the elements of the visual system considered as a long-period spectroscopic binary.

By adding 180° to the longitude $\omega=47°$ of the periastron, counted from the ascending node of B, we have the longitude of periastron, $\omega=247°$, counted from the ascending node of A in the long-period orbit. Figure 6 represents the theoretical velocity-curve of a spectroscopic binary characterized by the elements:

$$\omega=247°$$
$$e=0.72\ .$$

The scale of time attached to this curve is chosen in such a way that the period and the epoch of periastron passage correspond to

$$P = 6.88 \text{ years}$$

$$T = 1905.27 ,$$

respectively.

The scale of radial velocities can be derived from the extreme values of the radial velocity of the center of mass A of the spectroscopic binary corresponding to the epochs of its passage through the nodes of the orbit it describes around the center of mass of the visual

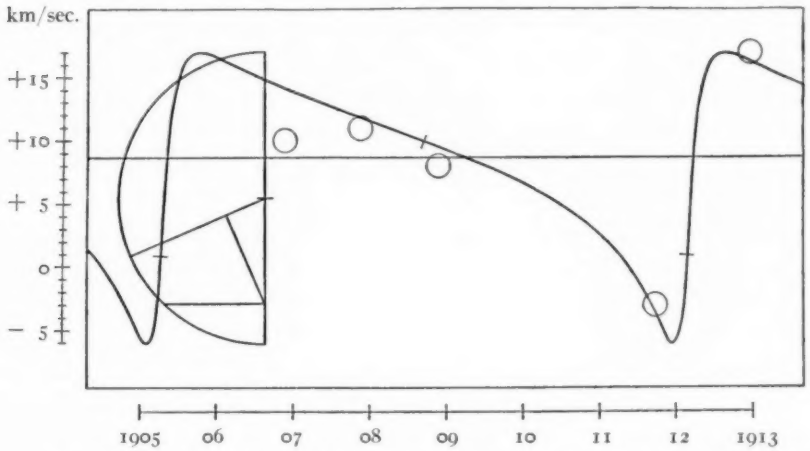


FIG. 6.—Theoretical long-period radial-velocity curve of 13 Ceti A corresponding to Aitken's elements.

system. The Lick spectrograms of 1911.72, preceding the epoch of passage of A through the descending node (1911.98), give a value of γ of about -3 km/sec. The Yerkes spectrograms of 1912.97, secured shortly after the epoch of passage of A through the ascending node (1912.64), give a velocity of recession of A of about 17 km/sec. Figure 6 shows that the negative velocity at the descending node should exceed the Lick velocity by about one-seventh of the observed range of 20 km/sec. We therefore take

$$2K_A = 23 \text{ km/sec.}$$

as an approximate value of the amplitude of oscillation of the theoretical velocity-curve of the seven-year spectroscopic binary Ho 212.

On the adopted scale of radial velocities, the diameter of the hodographic circle represents 23 km/sec., and the half-chord through the origin, i.e., at a distance 0.72 K_A from the center, corresponds to 8 km/sec. The length of the major semiaxis of the inclined orbit of A around the center of mass of the visual system is, therefore,

$$a_A \sin 53^\circ.45 = 8 \cdot 13750 \cdot 6.88 \cdot 365 = 276{,}000{,}000 \text{ km} ;$$

hence the mean distance,

$$a_A = 344{,}000{,}000 \text{ km or } 2.3 \text{ astronomical units} .$$

If we take $\pi = 0''.05$ as the value of the parallax of the system, the length of the major semiaxis of the true orbit of B around A is 4.8 astronomical units, and the mass-ratio of the visual system is

$$\frac{M_B}{M_A} = 0.92 .$$

The function of mass, as derived from the half-chord through the origin of the hodograph, is

$$\frac{(M_B \sin 53^\circ.45)^3}{(M_A + M_B)^2} = 8^3 \cdot 1.04 \cdot 10^{-7} \cdot 6.8 \cdot 365 \cdot = 0.133 \odot ,$$

whence

$$M_A = 1.22 \odot$$

$$M_B = 1.12 \odot .$$

Comparing the total mass of the system 13 Ceti,

$$M_A + M_B = 2.34 \odot ,$$

obtained by the spectro-visual method, with the result given by the dynamical method, $2.39\odot$, we see that the assumed range of the radial velocities of the center of mass of the spectroscopic binary at the nodes of its long-period orbit was justified.

The mass-luminosity curve gives, for $M_A = 1.22\odot$, the absolute magnitude 3.8. We have seen that the Mount Wilson value of the absolute magnitude, calculated from line-intensities, is 3.8 for the bright component of the visual system; the corresponding spectroscopic parallax is, however, $\pi_{sp} = 0''.042$.

The variations of γ, as derived from our spectrograms, seem to be more complicated than a simple elliptic motion with a period of 6.88 years could account for. The range $2K_A$ of γ at the nodes, corresponding to successive periastron passages, apparently varies, but its mean range seems to be of the order of 20 or 25 km/sec., if the close agreement of the dynamical and spectro-visual estimations of masses can be regarded as a criterion.

XI. VELOCITY OF THE SPECTROSCOPIC BINARY A′A″

The values of γ collected in Table XI, and corresponding to the curves of Figures 2, 3, and 4, are plotted in Figure 7. The theoretical long-period velocity-curve gives a satisfactory representation of the γ-values of the first spectroscopically observed seven-year period; the observed γ-values of the following revolutions show considerable deviations from the theoretical velocity-curve.

Before we pass to the examination of the irregularities in the variation of the radial velocity of the spectroscopic system, we recall that the proper motion of the visual system AB appears to indicate a uniform and rectilinear eastward drift (0″.410 in 92°.8); measures of the optical pair AB–C show no accelerations or deviations in the motion of the center of mass of AB, since the beginning of observations, in 1877. The hypothesis that 13 Ceti AB is in orbital motion with an outside dark body D, can therefore be dismissed, even if we are as yet unable to assign a constant value to the undoubtedly positive radial velocity γ_0 of the center of mass of the visual system.

On the other hand, the micrometric observations, both preceding and following the determination of the visual orbital elements by Mr. Aitken, establish a simple elliptical motion of B and A around their common center of mass; the hypothesis of the presence of a dark body D, in orbital motion with either A or B, should therefore be dismissed, since an additional orbital motion, capable of producing the large additional fluctuations of the values of γ, could hardly remain imperceptible on a diagram showing the observed position angles and distances of the system Ho 212.

The values of γ, represented in Figure 7, and weighted in Table XI, do not correspond to the theoretical velocity-curve derived from visual observations of the system AB.

When the spectroscopic binary A is between the apastron and the descending node of its visual orbit, as in 1910.93, 1917.06, 1917.83, and 1923.72, the observed values of γ are decidedly higher than could be expected, unless the observed values of γ corresponding to 1906.90, 1907.87, 1912.97, 1919.98, 1926.87, and 1927.95 are considerably below normal. The first set corresponds to the approach of A toward the plane of the sky passing through the center of mass of the visual system; the radial velocities of A should, in that part of the visual orbit, be less than the velocity of recession, in the line of sight, of the system AB; they should, therefore, be considerably less than the γ-values of the second set, which should obviously exceed

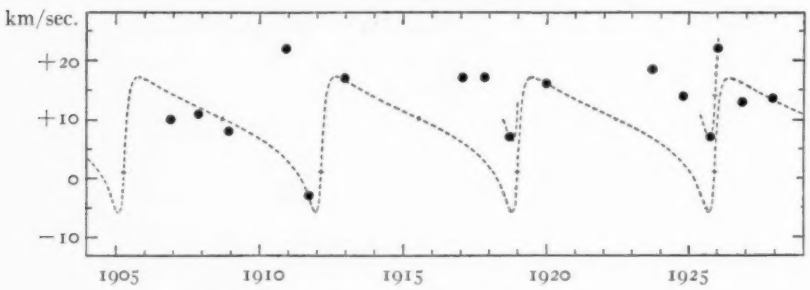


FIG. 7.—Values of γ of Figures 2, 3, and 4

the radial velocity of the center of mass of the system AB since they correspond to the recession of A from the ascending node. The first set should also show smaller values of γ than the radial velocity of A derived from the observations of 1908.89, corresponding to the slow orbital motion in a direction roughly parallel to the line of nodes.

The large velocities of recession observed in 1923.72 and 1917.06 remove the doubt as to the reliability of the two isolated couples of observations, 1910.93 and 1917.83, corresponding to the same region of the visual orbit. The question of periodicity of apparently abnormally large velocities of recession between apastron and descending node can be settled during the oppositions of 1930 and 1931.

Additional evidence of irregularities in the variations of the quantity which should, theoretically, represent the radial velocity of A is offered by the observations corresponding to passages of A

through the descending node. The value of γ derived from the Yerkes observations of 1925.75 is considerably larger than the γ-value derived from the Lick measurements of spectrograms secured shortly before the epoch of the descending node of 1911.98. The Mount Wilson spectrogram of 1918.71 fits the Yerkes curve of 1925.75, so that we can assume that the smallest γ-value corresponding to the epoch of the nodal passage of 1918.86 was of the same

TABLE XI

VALUES OF γ AND K OF FIGURES 2, 3, AND 4

EPOCH	γ	K	WT.	NO. OBS.	INTERVAL		PLATES
					Days	Periods	
1906.90.....	+10.0	36.5	.75	8	115.74	55.6	2–9
1907.87.....	+11.0	36.5	.75	10	83.83	40.3	10–19
1908.89.....	+ 8.0	37.0	1	12	110.67	53.2	20–31
1910.93.....	+22.0	.....	.25	2	13.99	6.7	33, 34
1911.72.....	− 3.0	38.0	.50	5	82.81	39.7	35–39
1912.97.....	+17.0	34.5	.75	10	72.86	35.0	40–49
1917.06.....	+17.0	42.0	.50	5	33.02	15.8	50–54
1917.83.....	+17.0	.....	.25	2	113.68	54.6	55, 56
1918.71.....	+ 7.0	.....	.25	1	.....	.....	57
1919.98.....	+16.0	35.0	.50	4	18.01	8.6	58–61
1923.72.....	+18.4	41.6	1	15	73.76	35.4	63–77
1924.81.....	+14.0	.....	.25	2	5.98	2.9	78, 79
1925.75.....	+ 7.0	35.0	.50	5	59.89	28.8	80–84
1926.02.....	+22.0	.....	.25	1	.....	.....	85
1926.87.....	+13.0	40.0	.75	6	90.84	43.5	86–91
1927.95.....	+13.5	37.1	1	19	105.80	50.8	92–110

NOTE.—Weights were assigned according to the quality and number of observations, their distribution in phase, the scattering in radial velocities, and the shortness of the interval covered.

order as at the following epoch of 1925.74, not of the order of the velocity of approach indicated by the Lick spectrograms for the preceding epoch of 1911.98.

A further feature of the apparently abnormal variations of γ seems to be a reduced value of the velocity of recession, soon after the passage through the ascending node, as suggested by the observations of 1906.90 and 1926.87.

It is obvious that the values of γ derived from the short-period oscillations cannot be considered as radial velocities of the center of mass of the spectroscopic binary A. Some of the possible interpreta-

tions should be mentioned even in the present state of our knowledge of the system 13 Ceti: if the measured spectrum belongs to A alone, then the values of K and γ derived from the short-period oscillations are affected by more or less periodical physical changes in the atmospheres[1] of the two components A′ and A″, or at least in the atmosphere of A′, if the spectroscopic companion is too faint; if the measured spectrum was impressed by the combined light of both components of the visual system, then the blend-effect is possibly the result of the binary nature of the visual companion B, and the superposed period of oscillation of γ values can be expected to be a simple function of the difference between the known short period of A′A″ and the hypothetical short period of B′B″;. O. Struve suggests that the blend-effect may depend on the position angle of the visual binary with respect to the orientation of the slit of the spectrograph.

The available spectrographic material is not sufficient for the establishment of the periodicity of the deviations of the γ-values from the theoretical velocity-curve.

XII. AMPLITUDE OF THE OSCILLATIONS OF SHORT PERIOD

The inspection of the curves of Figures 2, 3, and 4 shows that the amplitude $2K$ apparently changes, the maximum value ($K > 41$ km/sec.) corresponding to 1917.06 or 1923.72, and the minimum ($K < 35$ km/sec.), to 1912.97.

The latter value could be interpreted as a result of a contraction of the spectroscopic orbit near the periastron of the visual orbit, or as a change in the relative inclination of the spectroscopic and the visual orbits, or as a result of a simultaneous change of a and i, since we suppose that the period $P = 2^{d}08186$ is constant, and the eccentricity is negligible, in the formula

$$K\sqrt{1-e^2} = \frac{2\pi}{86{,}400\ P^{\text{days}}}\, a \sin i\,,$$

giving the mean orbital velocity as product of the mean instantaneous motion and the function of mean distance.

[1] See, e.g., P. Guthnick's papers in *Veröffentlichungen der Universitätssternwarte zu Berlin-Babelsberg*, **2**, Heft 3, 1918; *Die Naturwissenschaften*, **6**, 716, 1918; *Astronomische Nachrichten*, **208**, 171, 1919.

If such an interpretation is admissible, it would be logical to expect a maximum of the amplitude of the short-period oscillations at the apastron of the long-period orbit. The orbit of 1908.89 shows, however, the normal value of K. On the other hand, in 1917.06, 1923.72, and 1926.87, far from the respective apastra, the values of the amplitude appear to be considerably above the average, while the observations of 1925.75 show the normal value of K near periastron.

It is reasonable to assume that the apparent changes in K do not depend directly on the position of A in its long-period orbit. The reality of the changes in K appears doubtful, since appreciable variations of some of the elements of the spectroscopic orbit could hardly be compatible with the constancy of the period established by about 3750 revolutions.

The orbits of 1917.06 and 1923.72 appear to show a connection between large values of K and large values of γ; on the other hand, the large values of K corresponding to the orbits of 1911.72 and 1926.87 do not appear to confirm such a connection.

The available data are not sufficient to establish the periodicity of the apparent changes of K and their relation to the abnormal variations of γ. We can, however, consider their nature from the viewpoint of the origin of the measured spectrum.

If the measured spectrum belongs to A only, the apparent changes of K may be the result of physical changes in the atmospheres of A′ and A″ (or in the reversing layer of A′ only), superposed on the Doppler effect due to orbital motions. The variations of the amplitude of the short-period oscillations thus could be real, and more or less periodic, without concomitant changes in the elements of the spectroscopic orbit.

If we suppose, on the other hand, that the measured spectrum of 13 Ceti is a blend of the spectra of both components of the visual system, then the apparent changes of K are probably of instrumental, not of stellar origin. When the improvement of the spectrographic equipment will make it possible to observe the spectra of A and B separately, the amplitude of the short-period oscillations of A will probably be found to be as constant as their period, and the variations of the radial velocity of A will probably follow the

theoretical velocity-curve derived from micrometric and interferometric observations; it would not be surprising to find that B, similar to A in brightness and mass, is a spectroscopic binary characterized by orbital elements similar to those of A.

Additional observational material—astrometric, photometric, and spectrographic—will be necessary for the better understanding of the constitution of the multiple star Ho 212 = 13 Ceti AB.

A summary of the conclusions reached in this study is given in the abstract preceding this paper.

YERKES OBSERVATORY
April 1928

NOTE ADDED AUGUST 30

The desirability of interferometric and photometric observations of 13 Ceti is shown by the papers of M. Maggini[1] and of P. Slavenas,[2] dated February, 1928, and published in August.

Maggini suspects that the visual companion has an invisible satellite and describes a secondary long-period orbit, with a radius of about 0".03 or 0".04.

According to Slavenas, the light of 13 Ceti may vary, with a period of $0^d.4692$ and an amplitude of nearly 0.2 mag. His data indicate J.D.2425186.808 as the epoch of maximum.

[1] "Orbita del sistema βGC 314 = 13 Ceti dedotta da misure interferometriche," made at Catania with the Merz 13-inch refractor, and at Collurania with the Cooke 15½-inch. *Astronomische Nachrichten*, **233**, 97, 1928.

[2] "A Photometric Study of Uranus," made at the Yale University Observatory. *Ibid.*, p. 125, 1928.

THE CONTOURS OF THE HYDROGEN LINES OF SIRIUS AND OF OTHER A-STARS

By C. T. ELVEY

ABSTRACT

The *contours of the hydrogen lines* of Sirius have been obtained from density-curves of single-prism spectrograms. An empirical equation of the type $I=I_0e^{-kx}$ represents quite accurately the contours of the lines. A comparison of the observations is made with an *equation of resonance absorption* derived by H. von Klüber.

The equations are given for the contours of the hydrogen lines of twenty other stars which are being published in the *Annals of the Dearborn Observatory*.

The numerous theoretical and experimental investigations concerning the relation of the distribution of intensity within a spectral line to the physical conditions of the emitting or absorbing gases makes it very desirable to obtain more quantitative data on the contours of the lines in stellar spectra. Such data will be useful in the interpretation of the structure of the stellar atmospheres.

The particular spectrogram of Sirius chosen was No. 1290, April 19, 1928, made with the single-prism spectrograph attached to the 18½-inch refractor of the Dearborn Observatory. The spectrograph will be described by Professor Fox in the *Annals of the Dearborn Observatory* (**4**, Part 1). The scale of the spectra is: 61, 39, 31, and 27 A per mm at $H\beta$, $H\gamma$, $H\delta$, and $H\epsilon$, respectively. The slit width used was 0.05 mm and the length of the slit was 0.9 mm, which, owing to the reduction by the optical system, gave spectra 0.6 mm wide. The spectrograms were taken on Eastman 40 plates, and were standardized by exposures in a rotating sector sensitometer made by Gaertner.

The intensity-curves were obtained with the registering microphotometer of the Yerkes Observatory, which Professor Frost very kindly put at my disposal. The microphotometer was constructed in their shops and was put into operation in 1926 by the writer. Its optical features are similar to those of the Moll registering microphotometer. The receiving element is a ten-junction *Ag-Bi* thermopile by Coblenz, and the E.M.F. is measured with a Leeds and Northup high-sensitivity galvanometer. An image of the spectro-

gram, enlarged twenty fold, is projected upon the thermopile. The analyzing slit just in front of the thermopile was made parallel to the spectral line, and was opened to a width of 0.3 mm; thus a strip of spectrum varying in width from 0.9 A at $H\beta$ to 0.4 A at $H\epsilon$ is on the thermopile at any one time. The plate is driven past the beam of light at such a rate as to permit the registering of the galvanometer, which has a period of six seconds.

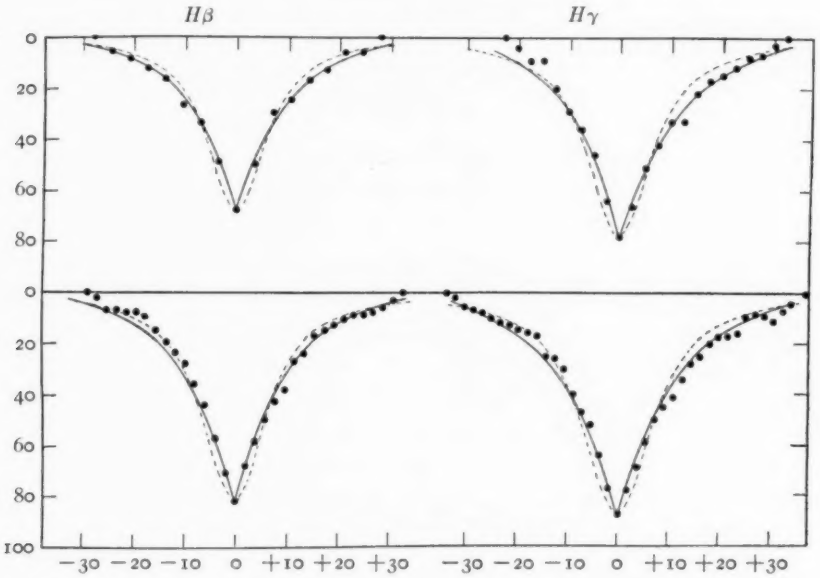


FIG. 1.—Contours of the hydrogen lines of Sirius. Continuous curves represent the empirical formula $I = I_0 e^{-kx}$; the broken lines, the formula of Klüber for resonance absorption.

The method used in reducing the galvanometer deflections to percentages of absorption of the continuous spectrum has recently been described by Theodore Dunham, Jr.[1]

The data for the hydrogen lines $H\beta$, $H\gamma$, $H\delta$, and $H\epsilon$ are plotted in Figure 1, the abscissae being $(\lambda - \lambda_0)$ (λ_0 is the wave-length of the center of the line). The ordinates are percentages of absorption of the continuous spectrum. It is seen that the lines are symmetrical excepting for $H\gamma$. This is no doubt due to a defect noticed just to

[1] *Harvard Bulletin No. 853.*

the violet side of the center of the line. There are indications of a faint line in the red wing of $H\gamma$ which is probably the *Cr-Mg* line at λ 4352. A smooth curve has been drawn over the two silicon lines, λ 4128 and λ 4131, to prevent their effect on the contour of the red wing of $H\delta$.

As the contours of the lines resemble the logarithmic curve, at the suggestion of Professor Fox, they were plotted, on semi-log-

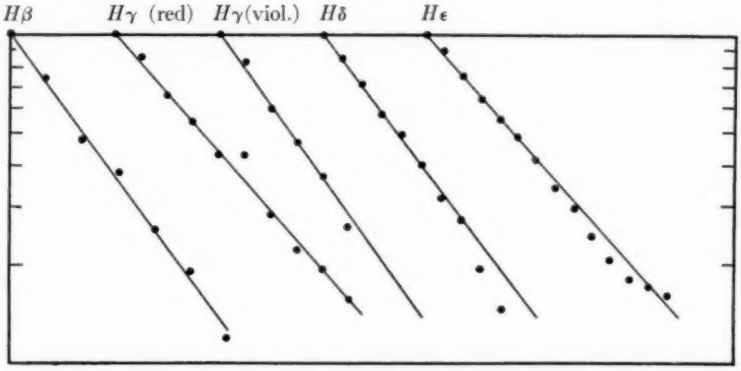


FIG. 2.—Contours of the hydrogen lines on semi-logarithmic paper

arithmic paper. The ratios of intensity (I) at (λ) to the intensity (I_0) at the center of the line (λ_0) are plotted as ordinates on the logarithmic scale and the distances from the center of the line in Angstrom units as abscissae on the linear scale (Fig. 2). Except in the case of $H\gamma$ the means of the intensities on the two sides have been taken. As the points on semi-log paper are closely represented by straight lines we can adopt the equation

$$I = I_0 \, e^{-k(\lambda - \lambda_0)}.$$

Taking k directly from the graphs and I_0 from the intensity-curves, the contours of the lines are computed. The continuous lines in Figure 1 represent the intensities according to this empirical equation. The equations are:

$$H\beta,\ I = 68\ e^{-0.098\,(\lambda - \lambda_0)}$$
$$H\gamma,\ I = 78\ e^{-0.095\,(\lambda - \lambda_0)}\ \text{(red side)}$$
$$H\gamma,\ I = 78\ e^{-0.084\,(\lambda - \lambda_0)}\ \text{(viol. side)}$$
$$H\delta,\ I = 82\ e^{-0.075\,(\lambda - \lambda_0)}$$
$$H\epsilon,\ I = 88\ e^{-0.084\,(\lambda - \lambda_0)}$$

Theodore Dunham, Jr.,[1] has recently published his measures of the contours of the hydrogen lines of several stars from objective-prism spectra taken at Harvard Observatory, and these for Sirius seem to agree quite well with his excepting at the center of the line. His measures give a somewhat smaller percentage of absorption.

In my investigation of the contours of the hydrogen lines in A-type stars which will be published in detail in the *Annals of the*

TABLE I

Star	M.	$H\gamma$		$H\delta$		$H\epsilon$	
		I_0	k	I_0	k	I_0	k
θ Aur	−1.3	78	0.161	81	0.159	89	0.147
α^2 CVn	−1.2	74	0.139	75	0.143	76	0.139
β Aur	−0.2	72	0.100	67	0.116	69	0.117
β Aur	−0.2	66	0.094	65	0.092	71	0.092
θ Hyd	0.0	75	0.092	78	0.095	84	0.105
γ Gem	0.1	71	0.141	72	0.137	87	0.135
α CrB	0.4	64	0.093	64	0.120	68	0.124
γ CrB	0.5	58	0.126	61	0.137	65	0.135
ϵ Aqr	0.5	77	0.100	77	0.105	.....	.....
α Lyr	0.6	73	0.105	70	0.096	74	0.104
δ Cyg	0.9	72	0.105	74	0.097	72	0.135
β Eri	1.0	69	0.089	67	0.117	.....	.....
α And	1.1	58	0.212	60	0.190	66	0.166
η Vir	1.2	71	0.133	75	0.147	80	0.120
λ Gem	1.5	57	0.139	70	0.105	.....	.....
δ Leo	2.1	73	0.124	67	0.100	78	0.120
80 UMa	2.1	58	0.127	54	0.102	61	0.116
α Cep	2.2	64	0.100	69	0.107	.....	.....
α Aql	2.5	61	0.121	65	0.105	77	0.096
ϵ Cyg	.....	52	0.106	57	0.139	.....	.....

Dearborn Observatory (**4**, Part 2), the data for twenty stars will be given. The equations of the contours of the $H\gamma$, $H\delta$, and $H\epsilon$ lines have been determined, using the same procedure as above. Table I contains the data for the equations. There is some deviation of the contours from the simple exponential equation, but in general the agreement is good.

There are many causes for the widening of stellar spectral lines, and probably the exact contour of a line will be explained by a combination of these causes. The widening due to the Doppler effect of the velocity of thermal agitation of the atoms has been investigated

[1] *Harvard Bulletin No. 858.*

by A. A. Michelson[1] and by many others. The equation of the contour of a line produced under this condition is that of the probability curve.

Another cause of broadening of a spectral line is the Stark effect, which has been discussed by several investigators. Nicholson and Merton[2] were able to represent quite accurately the contour of the *Hα* line as produced in their experiments by combining the Stark components of the line on the assumption that the distribution of intensity within each component is of the form

$$I = I_0^{-qx},$$

where x is the distance from the center of the component. They prove in general that the contour of the line will always be convex to the axis of symmetry, but the curve will have points of discontinuities to form little peaks which represent the positions of the components of the line. For a stellar absorption line it would be necessary to assume a distribution of the radiating or absorbing atoms with respect to the charged particles and to sum the intensities of all the possible components.

E. O. Hulburt[3] makes further experiments on the broadening of hydrogen lines due to the Stark effect. He finds that his data fit well with an approximate formula he derives for the distribution of intensity within the line,

$$I = gp^2/\ (\lambda_0 - \lambda),$$

where g is a constant which can be calculated, and p is the pressure expressed in atmospheres. An equation of this type will not fit the contours of the wide stellar lines when one uses pressures of the order thought to exist in the stellar atmospheres. In the derivation of the equation the assumption is made that the charged particles are the radiating atoms. This is a satisfactory approximation for the discharge tube in the laboratory, but it cannot be assumed to hold in the atmosphere of an A-type star.

H. von Klüber,[4] in a quantitative investigation of absorption lines of the sun, develops from the classical electron theory an equation

[1] A. A. Michelson, *Phil. Mag.*, **34**, 280, 1892; *Ap. J.*, **2**, 251, 1895.

[2] J. W. Nicholson and T. R. Merton, *Phil. Trans. Roy. Soc.*, A, **216**, 459, 1916.

[3] *Phys. Rev.*, **22**, 24, 1923. [4] *Zeit. f. Phys.*, **44**, 481, 1927.

for the distribution of the intensity within an absorption line. His formula for resonance absorption is

$$2n^2\kappa=\frac{\rho'\nu'}{\omega_0\,(4\delta^2-\nu'^2)}$$

where

$$\rho'=\frac{4\pi Ne^2q}{m.}$$

$$\nu'=\frac{b}{m}$$

n, index of refraction
κ, index of absorption
ω_0, frequency of the electron
c, the velocity of light
δ, $(\omega_0-\omega)$
N, Avogadro's number
e, charge on the electron
m, mass of electron
q, number of resonators
b, damping coefficient

Applying this equation to the absorption lines of Sirius, the constants can be determined empirically from the data and the contours of the lines can be computed. The dotted lines in Figure 2 represent the contours according to this equation. The agreement is not as good as might be wished, but then no account has been taken of the Doppler effects of thermal agitation, convection currents, and the rotation of the star, and of the other possible causes of broadening of a spectral line.

No attempt is being made to evaluate the quantities of physical interest involved in the formula, for it seems advisable to obtain the contours of the lines, especially the central portions, with higher dispersion and with a microphotometer of greater resolving power. The writer expects to be able to do this with a three-prism spectrograph of the Yerkes Observatory, and it is hoped that it will be possible to determine whether the agreement of the observation with theory is good enough to justify the evaluation of the constants giving some of the properties of the atmosphere of the star.

DEARBORN OBSERVATORY
June 13, 1928

THE PRESENCE OF PREDICTED IRON LINES IN THE SOLAR SPECTRUM AND THE TERMS IN THE ARC SPECTRUM OF IRON[1]

By CHARLOTTE E. MOORE and HENRY NORRIS RUSSELL[2]

ABSTRACT

The predicted lines.—The positions of lines which should occur in the multiplets of *Fe* but have not been observed in the laboratory have been calculated. A search in the solar spectrum has revealed 289 of these lines among the previously unidentified solar lines and 41 others not completely accounted for by other elements; 57 of the predicted lines have been measured on plates of the *Fe* arc taken with a long exposure. The solar wave-lengths and intensities and the multiplet designations are given in Table I.

Terms of Fe I.—All the known *Fe* terms and combinations are listed in Table II. Here the terms are counted upward from the zero level a^5D_4 and a uniform spectroscopic notation has been adopted, although the arbitrary symbols formerly used are also included. Improved term values derived from measures by H. D. Babcock of *Fe* standards on the neon scale are given for 25 terms.

The abundance of known iron lines in the solar spectrum suggests the presence of many which have not been observed in the laboratory. An examination of all the known multiplets of *Fe* indicates the absence of many faint satellites and of many lines belonging to inter-system combinations. From the known term values, the predicted positions of these lines have been calculated according to the quantum rules and a search for them in the solar spectrum has been made. In this way 289 solar lines previously unidentified and 41 others not wholly accounted for by other elements have been identified as due to *Fe*, as they fit into the multiplets with as much accuracy as do many observed *Fe* lines.

The lines are listed in Table I, the first column giving the wave-length of the solar line on the international scale; the second, the difference between the solar wave-length and that computed from the term values in Table II, expressed in hundredths of an angstrom. The third column contains the Rowland intensity, -1 being used for Rowland's 00, -2 for 000, etc.; the fourth gives the wave-number ν in vacuum; the fifth, the multiplet designation; and the last column, the identification adopted for the solar line in the *Re-*

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 365.

[2] Research Associate of the Mount Wilson Observatory, Carnegie Institution of Washington.

TABLE I

PREDICTED *Fe* LINES

λ I.A.	Δλ O−C (0.01Å)	Int.	ν Vac.	Multiplet Designation	Identification in the Sun
3146.467*	0	0	31772.47	$a^7D'_4-(ty_3)$	*Fe*
3176.446	−2	−1	31472.61	$a^3P'_2-(kx_3)$	*Fe?*
3202.668	+2	0	31214.96	$a^3F'_2-d^5D'_2$	*Fe*
3230.098	+1	0	30949.89	$a^5F'_3-b^3D'_2$	*Fe*
3241.490*	−1	0	30841.14	$a^5F'_1-b^3D'_1$	*Fe*
3261.818	+1	−1	30648.92	$a^3F'_3-b^5G'_2$	*Fe*
3305.751	−2	0	30241.64	$a^3F'_2-b^5G'_2$	*Co Fe*
3369.152	+1	0	29672.58	$a^3H'_4-(ix_5)$	*Fe*
3407.502	+2	3	29338.12	$a^5P'_3-(cx_2)$	*Fe−*
3450.141	+1	−1	28976.06	$b^3F'_3-(kx_3)$	*Fe*
3459.281	−1	−2	28899.50	$a^5D'_1-z^3D_1$	*Fe*
3473.011	0	−2	28785.25	$a^5D'_2-z^3D_2$	*Fe*
3473.228	−1	−3	28783.43	$a^5D'_4-z^3D_3$	*Fe*
3489.910	−3	−3	28645.86	$a^5D'_1-z^3D_2$	*Fe*
3502.470	0	−1	28543.14	$a^5D'_3-z^3D_3$	*Fe*
3551.113	−1 / +1	1	28152.20	$a^7F_4-(py_3)$ / $a^7F_6-(hy_5)$	*Fe*
3558.073	0	1	28097.13	$a^7F_3-(ry_2)$	*Fe*
3560.077	+2	−1	28081.27	$a^7F_3-(qy_{4,3})$	*Fe–CN*
3565.839	0	0	28035.90	$a^5D'_2-(a'y_2)$	*Fe*
3566.316	+1	0N	28032.13	$a^3P'_2-d^5P_1$	*Fe*
3579.836	+2	2	27926.27	$a^5D'_3-x^3G_4$	*Fe*
3582.332	−2	2	27906.86	$a^5D'_4-y^3D_1$	*−Fe*
3586.018	+2	1	27878.14	$a^7F_2-(ny_2)$	*Fe*
3592.900*	0	0	27824.76	$a^7F_6-(dy_5)$	*Fe–Y*
3595.684*	−1	−2	27803.25	$a^7F_1-(my_1)$	*Fe*
3599.545	0	−3	27773.36	$a^7F_3-(ky_2)$	*Fe*
3601.429	0	−2	27758.86	$a^3P'_2-d^5P_3$	*Fe*
3617.012	+2	0	27639.29	$a^7F_1-(ky_2)$	*Fe*
3618.305	−1	3	27629.36	$a^7F_5-(dy_5)$	*−Fe*
3618.924	+1	0	27624.71	$a^3P'_1-(fx_{17})$	*Fe*
3619.671	0	−1	27618.98	$a^3P'_1-b^3P_0$	*Fe*
3621.202	−1	2	27607.31	$a^5D'_3-y^3D_3$	*−Fe Co+*
3626.740	+3	2	27565.14	$a^5F_2-z^3D_2$	*Fe*
3635.829	+1	−1	27496.23	$a^7F_5-(ay_{6?})$	*Fe*
3638.169	0	1	27478.55	$a^7F_4-(dy_5)$	*Fe*
3643.812	−1	3	27436.01	$a^3F'_2-c^5D'_1$	*−Fe*
3647.563	−1	0	27407.81	$a^5D'_2-y^3D_3$	*Fe*
3651.040	+1	−1	27381.68	$a^5D'_4-y^5F'_4$	*Fe*
3655.356	0	1	27349.32	$a^3P'_1-b^3P_1$	*Fe*
3656.358	−1	1	27341.84	$a^7F_2-(ey_3)$	*Fe*
3673.774	+4	−3	27212.27	$a^5F_4-x^3G_3$	*Fe?*
3685.776	+2	−3	27123.61	$a^5F_2-z^3D_3$	*Fe*
3689.003	−2	1	27099.93	$a^3H'_5-(ax_4)$	*Fe*
3693.784	0	0	27064.87	$a^3F'_3-c^5D'_4$	*Fe*
3703.449	+2	−2	26994.20	$a^5F_4-(zy_3)$	*Fe*
3705.264	−2	−1N	26981.01	$a^5F_3-(a'y_2)$	*Fe*
3711.941	+1	0	26932.46	$a^3H'_4-(ax_4)$	*Fe Zr+?*
3717.188	0	−1	26894.42	$a^5F_5-(yy_4)$	*Fe*
3717.837	+2	0	26889.72	$a^7P_3-(ny_2)$	*Fe?*
3722.238	0	1	26857.93	$a^3P'_1-d^5P_1$	*Fe*

TABLE I—*Continued*

λ I.A.	Δλ O−C (0.01Å)	Int.	ν Vac.	Multiplet Designation	Identification in the Sun
3726.419.....	+2	−2d?	26827.81	$a^7P_2-(ty_3)$	*Fe*
3727.533.....	0	1	26819.81	$a^5F_2-x^3G_3$	*Fe*
3734.994.....	+3	−1	26766.25	$a^5F_1-(zy_3)$	*Fe*
3735.702.....	0	0Nd?	26761.16	$a^3P_1'-d^5P_2$	*Fe*
3741.481.....	−1	1	26719.82	$a^5F_1-y^3D_1$	*Fe V*
3743.781.....	0	1	26703.41	$a^7P_3-(ky_2)$	*Fe*
3758.131.....	+2	−1	26601.45	$a^5F_2-(zy_3)$	*Fe*
3761.069.....	−1	1	26580.65	$a^5F_4-y^3D_3$	*Fe*
3771.499.....	+1	1	26507.14	$a^5F_2-y^3D_2$	*Fe*
3785.792.....	+1	1	26407.09	$a^5F_5-y^5F_4'$	*Fe*
3796.017*....	−1	0	26335.93	$a^3H_6'-c^5G_5'$	*Fe*
3810.902.....	−2	0	26233.10	$b^3F_2'-c^3D_1'$	*Fe CN*
3813.930.....	−3	1	26212.27	$a^3H_5'-c^5G_4'$	*Fe*
3824.752.....	+1	−1	26138.11	$b^3F_2'-(fx_{17})$	*CN Fe*
3825.685.....	+2	1N	26131.69	$a^7P_2-(fy_{3,2})$	*CN Fe*
3826.627.....	−1	1N	26125.27	$a^3H_4'-c^5G_3'$	*Mn Fe*
3829.771*†...	0	1	26103.85	$b^3F_4'-(bx_3)$	*Fe*
3840.203.....	−1	0	26032.95	$a^3P_2'-d^5D_4'$	*Fe*
3842.905.....	0	1	26014.59	$b^3F_3'-(dx_4)$	*Fe*
3848.299†....	0	2	25978.16	$b^3F_2'-c^3D_3'$	*Fe–Ti*
3858.474.....	+1 0	0	25909.69	$a^5P_2-z^3D_1$ $a^5D_3'-y^5D_2$	*CN–Fe*
3867.442.....	−1	0	25849.59	$b^3F_2'-(cx_2)$	*Fe*
3878.196.....	+2	1	25777.88	$a^5D_4'-y^5D_4'$	*Fe*
3888.424.....	0	2	25710.13	$a^5D_2'-y^5D_2$	*−Fe*
3889.931†....	0	1	25700.15	$a^5D_2'-x^3D_1$	*Fe Ti Nd+*
3895.450.....	+2	3	25663.73	$a^5D_0'-y^5D_1$	*Fe−*
3896.624†....	−1	0	25656.02	$a^5P_2-z^3D_2$	*Fe*
3898.096.....	−4	2	25646.28	$a^5P_1-z^3D_1$	*−Fe?*
3901.062.....	+3	−2	25626.83	$a^5P_3-z^3D_3$	*Fe*
3905.191.....	−1	2	25599.73	$a^5D_3'-x^3D_2$	*−Fe*
3908.687.....	0	−1	25576.80	$a^7D_3'-x^5D_2$	*Fe*
3922.086.....	−1 +1	1	25489.42	$a^5D_0'-x^3D_1$ $a^7D_1'-x^5D_1$	*Fe Mn?*
3936.772.....	−3	0Nd?	25394.38	$a^5D_4'-x^3D_3$	*Mn Fe*
3937.143.....	+4	−1Nd?	25391.98	$a^5P_1-z^3D_2$	*Fe?*
3949.235.....	0	1	25314.19	$a^7D_1'-x^5D_2$	*Fe−*
3950.801.....	+2	−2	25304.19	$a^7D_3'-x^5D_3$	*Fe*
3955.768.....	−1	0	25272.40	$b^3F_4'-c^5G_4'$	*Fe*
3984.451.....	−3	−1	25090.49	$b^3F_3'-c^5G_2'$	*Fe*
3985.322.....	−3	1	25085.02	$b^3F_4'-c^5G_5'$	*Fe*
3992.646†....	0	0	25038.96	$b^3F_3'-c^5G_3'$	*Fe*
3994.272.....	0	−2	25028.81	$a^7F_2-x^5F_1'$	*Fe*
4006.159†....	−1	1	24954.53	$a^5D_2'-x^3D_3$	*Fe*
4033.190.....	0	1	24787.29	$b^3F_4'-b^3G_4'$	*Fe*
4036.377†....	0	0	24767.70	$a^3G_3-c^3D_3'$	*Fe*
4070.046.....	+4	0	24562.81	$a^7F_2-x^5F_3'$	*Fe*
4075.108.....	−4	2N	24532.31	$a^7F_5-x^5F_4'$	*−Fe*
4081.266.....	+4	1	24495.29	$a^3G_3-(bx_3)$	*Fe−*
4090.326†....	−1	0N	24441.09	$a^3F_2'-b^5P_1$	*Cr–Fe*
4096.217.....	+1	1	24405.89	$a^5F_3'-a^3F_2$	*Fe*
4099.996.....	+2	0	24383.39	$a^5F_1-y^5D_2$	*Fe*
4100.350.....	0	0	24381.30	$a^7F_4-x^5F_4'$	*Fe*

TABLE I—*Continued*

λ I.A.	Δλ O−C (0.01Å)	Int.	ν Vac.	Multiplet Designation	Identification in the Sun
4108.303.....	−1	−2	24334.13	$a^5P_1-y^3D_2$	*Fe*
4117.743*....	+1	−2	24278.34	$a^5P_2-y^3D_3$	*Fe*
4119.672.....	+1	0	24266.97	$a^7F_3-x^5F'_4$	*Fe*
4126.857*†...	−1	1	24224.69	$b^3P'_1-b^3P_0$	*Fe*
4129.187*†...	−1	3	24211.02	$a^5F_2-y^5D_3$	*Cr Fe*
4137.984†....	+1	0	24159.59	$a^7F_5-x^5F'_5$	*Fe*
4138.857*†...	+1	0	24154.45	$a^3P'_2-c^5P_3$	*Fe*
4143.510.....	0	2	24127.35	$a^5F_4-x^3D_3$	*Fe*
4149.767†....	+1	2	24090.95	$a^5D_3-a^7P_2$	*Fe−*
4169.096.....	+1	−1	23979.26	$a^5F'_1-a^3F_2$	*Fe*
4173.151.....	−3	−1d?	23955.98	$a^5F_3-y^5D_4$	*Fe*
4180.404†....	−2	1	23914.44	$a^3G_4-c^5G'_3$	*CN–Fe*
4194.491†....	−3	0	23834.11	$a^3G_4-c^5G'_4$	*CN–Fe*
4212.043.....	−4	−1N	23734.80	$a^5F_2-x^3D_3$	*Fe?*
4213.422.....	−3	−1	23727.03	$a^3G_4-c^5G'_5$	*Fe*
4219.597.....	+2	−2	23692.28	$a^3D'_2-z^3D_1$	*Fe*
4264.634†....	−1	−1	23664.07	$a^3G_3-c^5G'_3$	*Fe*
4239.046.....	+2	−3	23583.57	$a^3G_3-c^5G'_4$	*Fe*
4248.416.....	+2	1	23531.56	$a^5F'_1-a^3D'_2$	*Fe*
4249.352.....	+3	−1	23526.41	$a^3P'_1-c^5P_1$	*Fe*
4260.735.....	+2	1	23463.52	$b^3P'_1-d^5P_1$	*Fe–Ti*
4271.637.....	0	0Nd?	23403.65	$a^5P'_2-c^5F_1$	*Fe*
4271.961.....	+1	1N	23401.90	$a^3H'_5-b^5G'_4$	*Fe*
4277.392†....	−2	0	23372.19	$b^3F'_2-d^5D'_1$	*Fe Zr+?*
4281.601†....	0	−1	23349.21	$a^3H'_4-b^5G'_3$	*Fe*
4292.136†....	+1	2	23291.87	$a^5P'_3-c^5F_3$	*Fe*
4311.449.....	+1	2	23187.55	$a^3D'_1-z^3D_2$	*CH Fe*
4313.037†....	−2	1N	23179.06	$a^3G_3-b_3G'_4$	*CH Fe*
4319.456†....	+1	0	23144.56	$b^3F'_2-d^5D'_2$	*Fe*
4323.372†....	0	0	23123.62	$a^3H'_4-b^5G'_5$	*CH Fe*
4329.552†....	0	−1	23090.62	$a^5P'_1-c^5F_2$	*Fe*
4335.918.....	+2	−1	23056.69	$a^3D'_3-x^3G_3$	*Mn? Fe*
4336.616.....	0	−1N	23052.97	$a^3D'_3-(a'y_2)$	*Fe*
4338.835.....	+1	0N	23041.18	$a^3P_0-c^5P_1$	*Mn Fe*
4348.340†....	+2	1N	22990.84	$a^3F_2-z^3D_2$	*CH Fe*
4377.377*....	+4	0d?	22838.32	$a^3D'_3-(zy_3)$	*Fe−*
4392.589*†...	+2	1	22759.24	$a^3F_4-x^3G_4$	*Fe?*
4404.105.....	0	−1	22699.71	$a^3D'_2-y^3D_1$	*Fe*
4405.035.....	+2	1	22694.92	$a^5D_3-a^7F_3$	*V Fe*
4405.420.....	+2	−1	22692.96	$a^3D'_2-x^3G_3$	*Fe*
4406.163.....	+2	0	22689.15	$a^3D'_2-(a'y_2)$	*Fe–V*
4407.276.....	+3	0N	22683.38	$a^5P_3-x^3D_2$	*Fe*
4415.788.....	+2	−1N	22639.67	$a^3P'_2-c^5F_2$	*Fe*
4428.551.....	−2	1d?	22574.44	$a^3F_3-x^3G_3$	*V–Fe*
4433.394.....	−1	−1	22549.79	$b^3G_3-(cx_2)$	*Fe*
4450.764†....	−1	−1	22461.79	$a^3F_4-(yy_4)$	*Ce+–Fe*
4453.841.....	+2	−2	22446.26	$a^3D'_3-(yy_4)$	*Fe*
4455.452.....	+2	−2N	22438.15	$a^3D'_4-(a'y_2)$	*Fe Cr?*
4461.822.....	+2	−2N	22406.11	$b^3G_3-(bx_3)$	*Fe*
4471.685†....	+1	0	22356.66	$a^5D_1-a^7F_1$	*Fe*
4471.810*....	+1	−1	22356.06	$a^3F_3-(zy_3)$	*Fe–Co?*
4472.544.....	+2	−1N	22352.41	$a^3F'_4-b^5F_3$	*Fe*
4490.236.....	0	−1	22264.30	$a^7F_1-x^5D_1$	*Fe*

TABLE I—*Continued*

λ I.A.	Δλ O−C (0.01A)	Int.	ν Vac.	Multiplet Designation	Identification in the Sun
4494.064†....	+1	1	22245.37	$a^3F_2-x^3G_3$	*Fe*
4494.869....	+4	−2	22241.38	$a^3F_2-(a'y_2)$	*Fe?*
4498.562.....	−4	−1N	22223.12	$a^7F_3-x^5D_2$	*−Fe*
4509.130.....	−1	−2	22171.03	$b^3F'_2-b^5G'_2$	*Fe*
4513.722†....	0	−1	22148.48	$b^3F'_3-b^5G'_4$	*Fe Ti?*
4515.178†....	+1	0	22141.32	$a^7F_2-x^5D_2$	*Fe−*
4538.604.....	+2	−1N	22027.07	$a^5F_2-(zy_3)$	*Ti? Fe*
4551.656*†...	+1	0	21963.87	$a^3F_3-(yy_4)$	*Fe*
4566.664.....	−3	−3	21891.73	$b^3F'_4-c^5P_3$	*Fe?*
4571.448†....	+1	0	21868.79	$a^7F_2-x^5D_3$	*Fe−*
4597.038.....	−2	−1	21747.05	$a^5F'_2-a^5P_1$	*Fe*
4598.374.....	+4	−1	21740.77	$a^5F'_3-a^5P_2$	*Fe?*
4611.194.....	0	0	21680.33	$a^7F_4-x^5D_4$	*Fe Cr?*
4615.940.....	+4	−1	21658.01	$b^3F'_3-c^5P_3$	*Fe?*
4625.440.....	−2	−1N	21613.53	$a^3F_2-y^3D_3$	*Fe*
4626.802.....	+1	−1	21607.18	$b^3G_4-c^5G'_5$	*Fe*
4631.039†....	0	0N	21587.39	$b^5D'_4-z^3D_3$	*Fe*
4633.777*†...	+2	0N	21574.63	$b^3G_3-c^5G'_3$	*Fe*
4635.630.....	+1	0	21566.02	$a^7F_3-x^5D_4$	*Fe−*
4642.593.....	−1	−1N	21533.69	$a^5F_3-x^3F'_2$	*Fe*
4643.217.....	+2	−1	21530.77	$a^3F'_4-b^5D'_3$	*Fe*
4653.505.....	+2	−1	21483.16	$a^5F'_2-a^5P_2$	*Fe*
4672.839.....	+1	1	21394.30	$a^3F'_2-a^3P_1$	*Fe*
4674.658†....	+1	0N	21385.96	$a^3F'_3-a^3P_2$	*Fe*
4678.422.....	−1	−1	21368.77	$a^5F_2-x^3F'_2$	*Fe*
4679.985.....	+1	−2	21361.61	$b^5D'_1-z^3D_1$	*Fe*
4687.313.....	+1	0	21328.24	$a^5F'_3-a^5P_3$	*Fe*
4688.382.....	0	0	21323.38	$b^5D'_2-z^3D_2$	*Fe−Ti*
4690.382†....	0	0	21314.29	$a^5F'_1-a^5P_2$	*Fe*
4700.441.....	+2	−1	21268.67	$a^5P'_2-b^3D'_1$	*Fe*
4701.910.....	−1	0N	21262.03	$a^5F_1-x^3F'_2$	*Fe*
4720.579.....	+2	−2	21177.93	$a^3P_2-z^3D_2$	*Fe?*
4736.234.....	−2	−3	21107.95	$b^5D'_1-z^3D_2$	*Fe*
4739.658.....	+3	−3N	21092.68	$a^3P'_0-c^5F_1$	*Fe?*
4744.644.....	0	−2	21070.54	$a^5F'_2-a^5P_3$	*Fe*
4787.509.....	−2	−3	20881.87	$b^5D'_2-z^3D_3$	*Fe*
4790.570.....	−2	−2	20868.53	$b^5D'_3-(a'y_2)$	*Fe?*
4794.365†....	+2	−1	20851.99	$a^3P'_1-c^5D'_1$	*Fe*
4799.071.....	−1	−3	20831.57	$b^5F_2-z^3D_1$	*Fe*
4807.228†....	0	−2	20796.20	$b^5F_3-z^3D_2$	*Fe*
4842.734.....	+2	−3	20643.76	$b^5F_4-z^3D_3$	*Fe*
4858.264.....	+1 −1	−2	20577.77	$b^5D'_2-x^3G_3$ $b^5F_2-z^3D_2$	*Fe*
4860.994†....	0	0	20566.21	$a^5F_3-x^3F'_4$	*Fe*
4862.553†....	+1	−2	20559.62	$b^5D'_3-y^3D_2$	*Fe*
4863.782.....	0	−3	20554.42	$a^7P_2-x^5D_3$	*Fe*
4867.544†....	+1	−1	20538.54	$a^3F'_2-b^5D'_3$	*Fe*
4877.592†....	−2	0	20496.22	$a^7P_3-x^5D_4$	*Fe*
4907.504.....	−3	−3	20371.30	$b^5F_5-x^3G_4$	*Fe*
4908.033†....	−3	0N	20369.10	$b^5D'_1-y^3D_1$	*−Fe*
4908.608†....	0	−2	20366.70	$a^3P'_0-c^5D'_1$	*Fe*
4911.541†....	+1	0	20354.55	$b^5F_3-z^3D_3$	*Fe−*
4933.193.....	0	0	20265.22	$b^5D'_2-y^3D_2$	*Fe*

TABLE I—*Continued*

λ I.A.	Δλ O−C (0.01A)	Int.	ν Vac.	Multiplet Designation	Identification in the Sun
4968.395.....	+1	−1	20121.61	$b^5F_4-(zy_3)$	*Fe*
4968.854.....	+1	−3	20119.79	$a^3P_2-y^3D_2$	*Fe*
4980.305.....	+2	−2	20073.49	$b^5F_5-(yy_4)$	*Fe*
4985.992.....	+1	−1	20052.62	$b^5F_3-x^3G_3$	*Fe*
4986.915†....	−1	−1	20046.88	$b^5F_3-(a'y_2)$	*Fe*
4987.654.....	+3	−3	20043.95	$b^5F_5-x^3G_5$	*Fe*
4987.857.....	+3	−3	20043.10	$a^3F_4-y^5D_4$	*Fe*
4991.862†....	+1	−1	20027.04	$b^5F_4-x^3G_4$	*Fe*
4992.787.....	−2	−2	20023.31	$a^3P_1-y^3D_1$	*Fe*
5003.881.....	+1	−3	19978.94	$b^3F'_2-c^5F_2$	*Fe*
5006.695.....	−2	−2	19967.68	$b^3F'_3-c^5F_3$	*Fe*
5010.331†....	−1	−2	19953.22	$b^3F'_4-c^5F_4$	*Fe*
5012.160.....	−2	1	19945.93	$b^5D'_2-y^3D_3$	*−Fe*
5019.737.....	+1	−1	19915.81	$a^3F_2-y^5D_2$	*Fe*
5041.325.....	−2	−1	19830.52	$a^3P_0-y^3D_1$	*Fe*
5041.859.....	−2	−1	19828.44	$b^5F_2-(a'y_2)$	*Fe*
5064.975.....	+3	1	19737.93	$b^5F_3-y^3D_2$	*Fe−*
5069.627.....	+1	−3	19719.82	$b^3F'_3-c^5F_4$	*Fe*
5104.198.....	+1	0	19586.27	$b^5F_5-y^5F'_4$	*Fe*
5120.888.....	−2	−3	19522.43	$a^5G'_2-z^3D_1$	*Fe*
5123.290†....	+1	−3	19513.29	$a^5G'_3-z^3D_2$	*(C−)? Fe*
5127.690†....	+1	−1	19496.54	$a^5D_3-a^7D'_4$	*Fe*
5146.319†....	+2	−2	19425.96	$a^5G'_4-z^3D_3$	*Fe*
5159.971.....	+2	−2	19374.57	$b^5F_1-y^3D_2$	*Fe*
5172.219†....	0	−1	19328.69	$b^3F'_4-c^5D'_3$	*Fe*
5184.199.....	+4	−2	19284.02	$a^5G'_5-x^3G_4$	*Fe?*
5196.270.....	+4	−3N	19239.23	$b^3G_5-b^5G'_4$	*Fe*
5206.821.....	−1	−3	19200.25	$b^5F_2-y^3D_3$	*Fe*
5217.677.....	−3	−3N	19160.28	$a^3F_2-x^3D_3$	*Fe*
5226.388.....	−2	−3	19128.36	$b^3G_5-b^5G'_5$	*Fe*
5241.931*....	+2	−3	19071.65	$a^5G'_3-z^3D_3$	*Fe*
5253.040†....	0	−1	19031.32	$a^3P'_2-b^5P_1$	*Fe*
5261.503.....	0	−3	19000.71	$b^3G_5-b^5G'_6$	*Fe*
5265.424.....	−1	−3	18986.57	$a^5G'_5-(yy_4)$	*Fe*
5267.106.....	−4	−2	18980.47	$a^5P_3-x^5F'_2$	*Fe?*
5273.602.....	−3	−3N	18957.12	$a^5G'_5-x^3G_5$	*Fe*
5280.931.....	+1	−3Nd?	18930.80	$b^3F'_2-c^5D'_3$	*Fe*
5285.131†....	+1	0	18915.76	$a^3G'_4-z^3D_3$	*Fe*
5288.379.....	+2	−3	18904.14	$b^3G_4-b^5G'_4$	*Fe*
5318.040†....	+1	−3	18798.71	$b^3G_3-b^5G'_3$	*Fe*
5323.510*....	−1	−3	18779.39	$a^3P'_2-b^5P_2$	*Fe*
5327.895.....	+1	−1	18763.92	$a^5G'_3-(a'y_2)$	*Fe*
5331.197†....	0	−3	18752.30	$a^5P_2-x^5F'_1$	*Fe*
5346.341.....	0	−2	18699.20	$a^5P_3-x^5F'_3$	*Fe*
5384.204.....	−2	−3	18567.71	$a^5P_2-x^5F'_2$	*Fe?*
5429.513.....	0	1	18412.73	$b^5D'_2-y^5D_1$	*Fe*
5435.184.....	+1	−1	18393.56	$a^3G'_4-(zy_3)$	*Fe*
5437.209.....	+3	−1	18386.69	$a^5G'_5-(uy_6)$	*Fe*
5461.824.....	+2	−2N	18303.84	$a^5P_1-x^5F'_2$	*Fe*
5464.112.....	+1	−3N	19296.17	$a^3G'_3-(a'y_2)$	*Fe*
5521.141*....	−1	−1	18107.18	$a^5G'_4-y^5F'_3$	*Fe*
5528.905.....	+2	−1	18081.74	$a^3G'_3-(zy_3)$	*Fe*
5536.599.....	+3	−1	18056.62	$b^3P'_2-a^5S'_2$	*Fe?*

TABLE I—*Continued*

λ I.A.	Δλ O−C (0.01Å)	Int.	ν Vac.	Multiplet Designation	Identification in the Sun
5563.700.....	+1	0	17968.67	$a^3P'_1-b^3F_2$	*Co Fe*
5579.357.....	0	−2	17918.24	$b^5D'_0-x^3D_1$	*Fe?*
5650.287.....	−3	−3	17693.31	$b^3F_4-x^3G_3$	*Fe*
5651.477.....	+1	0	17689.58	$a^3G'_3-(yy_4)$	*Fe*
5658.672.....	−1	0	17667.13	$b^5F_2-y^5D_1$	*Cr? Fe*
5664.304.....	+3	−3	17649.36	$a^3G'_4-(wy_4)$	*Fe?*
5678.407.....	0	−2	17605.69	$a^3D'_3-x^3F'_2$	*Fe*
5678.616.....	+3	−2	17605.04	$a^3P'_1-b^5P_2$	*Fe*
5720.902.....	+2	0	17474.93	$b^3F_4-(zy_3)$	*Fe*
5747.865.....	+4	−2	17392.94	$b^3P'_2-c^5D'_2$	*Fe?*
5754.923.....	+4	−2N	17371.63	$a^3P'_0-b^5P_1$	*Fe?*
5759.550*†...	+1	0	17357.67	$b^5F_1-y^5D_2$	*Fe*
5762.847.....	−2	0	17347.73	$b^5F_1-x^3D_1$	*Fe*
5807.804.....	+1	0	17213.46	$a^5D'_0-x^7D_1$	*Atm.-Fe*
5807.995.....	−1	−1	17212.87	$b^3F_3-(a'y_2)$	*Fe*
5827.886.....	0	0	17154.13	$a^5D'_1-x^7D_2$	*Fe*
5835.589.....	+3	−2	17131.49	$b^3P'_2-c^5D'_3$	*Fe*
5838.385*....	−1	1	17123.27	$a^3F_3-x^3F'_2$	*Fe*
5864.252.....	−2	0	17047.76	$b^5F_1-x^3D_2$	*Fe*
5881.288.....	+2	0	16998.37	$b^3F_3-(zy_3)$	*Fe*
5881.728.....	−2	−2	16997.10	$a^5P'_3-b^5F_2$	*Fe*
5898.218*....	+2	−1	16949.58	$b^3D'_3-z^3D_2$	*Fe*
5943.602.....	+1	−1	16820.17	$a^5P'_2-b^5F_2$	*Fe*
5981.398.....	+5	−3	16713.88	$a^3D'_3-x^5F'_2$	*Fe?*
5986.134.....	+2	−2	16700.67	$b^3D'_2-z^3D_1$	*Fe*
6015.264.....	+1	−2	16619.79	$a^5P'_1-b^5F_2$	*Fe?*
6051.037.....	+3	−3N	16521.52	$b^3F'_4-b^3F_3$	*Fe*
6075.532.....	−3	−3	16454.93	$b^3F_3-(xy_3)$	*Fe*
6083.708.....	+3	−3N	16432.80	$a^3D'_3-x^5F'_3$	*Fe*
6097.106.....	+3	−3	16396.68	$a^5P'_3-a^3P_2$	*Fe*
6114.396.....	−1	−3N	16350.32	$a^3D'_2-x^5F'_2$	*Fe*
6120.257.....	+1	−1	16334.68	$a^5F'_4-a^7P_4$	*Fe*
6137.509.....	0	−2	16288.75	$a^5F_5-x^7D_4$	*Fe*
6171.010.....	−4	−3	16200.33	$b^3D'_3-(a'y_2)$	*Fe?*
6187.413.....	+2	−1	16157.39	$b^3P'_2-b^3D'_1$	*Fe*
6219.528.....	0	−3	16073.95	$a^5F_2-x^7D_2$	*Fe*
6253.847.....	+3	−1	15985.74	$b^3D'_3-(zy_3)$	*Fe*
6254.797.....	+4	−3N	15983.31	$a^5F'_3-a^7P_4$	*Fe*
6271.289*....	0	0	15941.29	$a^5F_5-x^7D_5$	*Fe*
6290.547.....	+5	−2N	15892.47	$b^3G_3-c^5D'_2$	*Fe?*
6310.493*....	−2	−3	15842.26	$b^3G_5-c^5D'_4$	*Fe*
6339.982.....	+2	−3	15768.57	$a^5F_3-x^7D_4$	*Fe*
6353.856.....	+2	−3	15734.12	$a^5F'_4-a^7F_3$	*Fe*
6367.146.....	+3	−2	15701.28	$b^3D'_2-x^3G_3$	*Fe*
6388.424.....	0	−2	15649.00	$a^5F_4-x^7D_5$	*Fe*
6411.125.....	+2	−2	15593.57	$b^3D'_3-(yy_4)$	*Fe*
6412.240.....	+2	−3	15590.87	$a^3H'_4-a^3G'_5$	*Fe*
6456.874.....	+1	−1N	15483.11	$b^3D'_2-(zy_2)$	*Fe*
6603.374.....	+4	−3N	15139.61	$a^3P'_1-b^5F_1$	*Fe?*
6613.817.....	−1	−1Nd?	15115.69	$a^5F'_1-a^7F_0$	*Fe*
6634.132.....	−1	0	15069.41	$b^3D'_2-y^3D_3$	*Fe*
6639.726.....	+1	0	15056.70	$b^5P_2-y^5D_1$	*Fe*
6648.130.....	+5	−2	15037.67	$a^5F'_1-a^7F_2$	*Fe?*

TABLE I—*Continued*

λ I.A.	Δλ O−C (0.01Å)	Int.	ν Vac.	Multiplet Designation	Identification in the Sun
6667.464.....	+3	−2	14994.08	$a^3H'_4-a^5G'_5$	*Fe*
6704.509.....	0	−2	14911.22	$b^5D'_4-x^3F'_3$	*Fe*
6746.984.....	+1	−2	14817.36	$b^3F'_3-a^5G'_2$	*Fe*
6801.859.....	−1	−3	14697.82	$a^3F'_2-a^5F_1$	*Fe*
6819.606.....	+1	−1d?	14659.56	$b^5D'_4-x^5F'_3$	*Fe*−
6822.053.....	+1	−3N	14654.31	$a^3P'_0-b^5F_1$	*Fe*
6844.695.....	+3	−3	14605.82	$a^3F'_3-a^5F_4$	*Fe*
6847.615.....	−1	−2	14599.59	$b^5F_3-x^3F'_2$	*Fe*
6851.664.....	+2	−2	14590.98	$a^3F'_2-a^5F_2$	*Fe*
6860.965.....	+4	−2	14571.18	$b^3P'_2-b^5P_1$	*Fe*?
6881.055.....	+2	−3N	14528.64	$b^3F_2-y^5D_2$	*Fe*
6933.052*....	+1	0N	14419.70	$b^5D'_2-x^5F'_1$	*Fe*
6937.942.....	0	−2	14409.54	$c^5D'_3-x^3G_3$	*Fe*
6951.647.....	0	−2	14381.11	$b^5F_2-x^3F'_2$	*Fe*
7022.409.....	−2	−2	14236.21	$b^5F_1-x^3F'_2$	*Fe*
7034.920.....	−3	2N	14210.89	$b^3P'_1-b^5P_2$	−*Fe*
7069.557.....	+1	−3	14141.26	$b^3F'_4-a^5G'_5$	*Fe*
7256.132.....	−5	−2	13777.66	$c^5D'_3-y^3D_3$	*Fe*?

* Measured to one decimal place by Kayser.
† Line measured on plate.

vision of Rowland's Table.[1] The parentheses in the fifth column indicate that the type of the term is undetermined and that an arbitrary symbol has been used.

Twenty-four of these predicted lines have been measured to one decimal place by Kayser.[2] Such lines are marked with an asterisk in Table I. In all but eight cases the solar wave-lengths are nearer the computed positions than Kayser's values.

An examination of one second-order plate of the *Fe* arc, λ 3800 to λ 4638, and two first-order plates, λ 4108 to λ 5780, having long exposures, which were kindly taken by A. S. King with the fifteen-foot concave-grating spectrograph, reveals the presence of some of the stronger predicted lines. Owing to the strong exposure, a number are masked by known lines, and measuring is difficult because the good standards are widened. Fifty-seven predicted lines have been measured, however, the average sun-arc residual being ±0.026 A. In identifying the measured lines as solar lines, no sun-arc residual

[1] *Carnegie Institution of Washington Publication*, No. 396; *Mt. Wilson Papers*, No. 3, 1928.

[2] *Handbuch der Spectroscopie*, **6**, 896, 1912.

TABLE II

Fe I TERMS AND COMBINATIONS

Symbol	Type	Term	Combinations				Symbol	Type	Term	Combinations			
D′	$a^3P'_2$	18378.22	a^3S'	a^3P	b^3P	a^3D'	f	$x^3F'_4$	47960.89	a^3D'	b^3D'	a^3F	b^3F
(1)		*174.25*	b^3D'	c^3D'	a^3F	b^3F	(3)		*570.93*	a^3G'	a^5D'	b^5D'	a^5F
	$a^3P'_1$	19552.47	a^5S'	a^5P	b^5P	c^5P		$x^3F'_3$	48531.82	b^5F	a^5G'		
		485.37	d^5P	e^5P	b^5D'	c^5D'			*396.51*				
	$a^3P'_0$	20037.84	d^5D'	b^5F	c^5F	(x)		$x^3F'_2$	48928.33				
							V′	a^3G_5	21715.78	b^3D'	c^3D'	b^3F	b^3G'
							(4)		*283.41*	a^3H	c^5G'	(x)	
e	$b^3P'_2$	22838.31	a^3S'	a^3P	b^3P	b^3D'		a^3G_4	21999.19				
(1)		*108.47*	c^3D'	a^5S'	b^5P	d^5P			*250.28*				
	$b^3P'_1$	22946.78	e^5P	b^5D'	c^5D'			a^3G_3	22249.47				
		104.90					h	b^3G_5	23783.63	b^3D'	c^3D'	b^3F	a^3G'
	$b^3P'_0$	23051.68					(1)		*335.17*	b^3G'	a^3H	c^5D'	a^5G'
q	x^3D_3	51294.19	a^3P	a^3D'	b^3D'	a^3F		b^3G_4	24118.80	b^5G'	c^5G'	(x)	
(1)		*445.67*	b^3F	a^3G'	a^5P	b^5P			*219.98*				
	x^3D_2	51739.86	a^5D'	b^5D'	a^5F	b^5F		b^3G_3	24338.78				
		299.99	c^5F										
	x^3D_1	52039.85					p	x^3G_5	53739.48	a^3D'	b^3D'	a^3F	b^3F
							(1)		*327.13*	a^3G'	a^5D'	b^5D'	c^5D'
								x^3G_4*	54066.61	a^5F	b^5F	c^5F	a^5G'
g	y^3D_3	53747.45	a^3P	a^3D'	b^3D'	a^3F			*312.81*				
(3)		*319.35*	b^3F	a^5P	a^5D'	b^5D'		x^3G_3	54379.42				
	y^3D_2*	54066.80	c^5D'	a^5F	b^5F	c^5F?	v	$a^3H'_6$	19390.20	a^3G'	b^3G'	a^3H	a^5G'
		319.30					(1)		*230.87*	b^5G'	c^5G'	(x)	
	y^3D_1	54386.10						$a^3H'_5$	19621.07				
									167.24				
i	z^3D_3	54683.37	a^3P	a^3D'	b^3D'	a^3F		$a^3H'_4$	19788.31				
(1)		*441.60*	b^3F	a^3G'	a^5P	a^5D'							
	z^3D_2	55124.97	b^5D'	a^5F	b^5F	c^5F	j	$a^3S'_1$	47555.53	a^3P'	b^3P'		
		253.81	a^5G'				(1)						
	z^3D_1	55378.78											
							K′	a^3P_2	33946.96	a^3P'	b^3P'	x^3D	y^3D
									415.93	z^3D	a^3F'	a^5P'	a^5D
C	$a^3F'_4$	11976.259§	a^3P	a^3D'	b^3D'	c^3D'		a^3P_1	34362.89	a^5F'	x^5F'		
		584.688	a^3F	b^3F	a^3G'	b^3G'			*192.77*				
	$a^3F'_3$	12560.947	a^3H	a^5P	b^5P	c^5P		a^3P_0	34555.66				
		407.615	a^5D'	b^5D'	c^5D'	d^5D'							
	$a^3F'_2$	12968.562	a^5F	b^5F	c^5F	a^5G'	m	b^3P_2	46727.10	a^3P'	b^3P'	a^5P'	a^5D
			b^5G'	c^5G'	(x)		(1)		*174.70*	a^5F'			
							(4)	b^3P_1	46901.80				
									269.74				
								b^3P_0	47171.54				
c	$b^3F'_4$	20641.18	a^3D'	b^3D'	c^3D'	a^3F							
(1)		*233.36*	b^3F	a^3G'	b^3G'	c^5P	Z	$a^3D'_3$	31322.640§	a^3P'	x^3D	y^3D	z^3D
	$b^3F'_3$	20874.54	c^5D'	d^5D'	b^5F'	c^5F	(2)		*363.729*	a^3F'	b^3F'	x^3F'	x^3G
		164.50	a^5G'	b^5G'	c^5G'	(x)		$a^3D'_2$	31686.369	a^5D	a^5F'	x^5F'	(y)
	$b^3F'_2$	21039.04							*250.968*				
								$a^3D'_1$	31937.337				

* The levels y^3D_3 and x^3G_4 are apparently coincident.

TABLE II—*Continued*

Sym-bol	Type	Term	Combinations				Sym-bol	Type	Term	Combinations			
P	$b^3D'_3$...	38175.379§	a^3P'	b^3P'	x^3D	y^3D	A	a^5D_4...	0.000§	a^5S'	a^5P	b^5P	c^5P
		502.682	z^3D	a^3F'	b^3F'	x^3F'			*415.930*	d^5P	e^5P	a^5D'	b^5D'
	$b^3D'_2$...	38678.061	a^3G	b^3G	x^3G	a^5P'		a^5D_3...	415.930	c^5D'	d^5D'	a^5F	b^5F
		317.699	a^5D	y^5D	a^5F'	(y)			*288.069*	c^5F	a^5G'	c^5G'	a^3P
	$b^3D'_1$...	38995.760						a^5D_2...	703.999	b^3P	a^3D'	b^3D'	c^3D'
									184.130	a^3F	b^3F	a^3G'	a^7P
								a^5D_1...	888.129	a^7D'	a^7F		
o	$c^3D'_3$...	47017.19	a^3P'	b^3P'	a^3F'	b^3F'			*89.938*				
(1)		*118.89*	a^3G	b^3G	a^5P'	a^5D		a^5D_0...	978.067				
(4)	$c^3D'_2$...	47136.08	a^5F'										
		135.94											
	$c^3D'_1$...	47272.02					T	x^5D_4...	44677.008§	a^5P	a^5D'	a^5F	b^5F
									384.321	a^7P	a^7D'	a^7F	
I	a^3F_4...	31307.264§	a^3P'	x^3D	y^3D	z^3D		x^5D_3...	45061.329				
		497.826	a^3F'	b^3F'	x^3F'	x^3G			*272.545*				
	a^3F_3...	31805.090	a^5D	y^5D	a^5F'	(y)		x^5D_2...	45333.874				
		328.916							*175.278*				
	a^3F_2...	32134.006						x^5D_1...	45509.152				
									85.925				
N	b^3F_4...	36686.202§	a^3P'	x^3D	y^3D	z^3D		x^5D_0...	45595.077				
		476.563	a^3F'	b^3F'	x^3F'	a^3G							
	b^3F_3...	37162.765	b^3G	x^3G	a^5D	y^5D	T′	y^5D_4...	51350.491§	a^5P	b^5P	a^5D'	b^5D'
		358.415	a^5F'	x^5F'	y^5F'	(y)	(2)		*420.081*	a^5F	b^5F	c^5F	b^3D'
	b^3F_2...	37521.180						y^5D_3...	51770.572	a^3F	b^3F		
									279.288				
								y^5D_2...	52040.860				
M	$a^3G'_5$...	35379.235§	x^3D	z^3D	a^3F'	b^3F'			*164.462*				
		388.349	x^3F'	b^3G	x^3G	a^3H'		y^5D_1...	52214.322				
	$a^3G'_4$...	35767.584	a^5D	a^5F'	x^5F'	y^5F'			*43.052*				
		311.801	(y)					y^5D_0...	52257.374				
	$a^3G'_3$...	36079.385					B	$a^5F'_5$....	6928.284§	a^5S'	a^5P	b^5P	c^5P
									448.488	e^5P	a^5D'	b^5D'	c^5D'
k	$b^3G'_5$...	45294.85	a^3F'	b^3F'	a^3G	b^3G		$a^5F'_4$....	7376.772	d^5D'	a^5F	b^5F	c^5F
(1)		*133.59*	a^3H'	a^5F'					*351.294*	a^5G'	b^5G'	c^5G'	a^3P
	$b^3G'_4$...	45428.44						$a^5F'_3$....	7728.066	b^3P	a^3D'	b^3D'	c^3D'
		134.56							*257.726*	a^3F	b^3F	a^3G'	b^3G'
	$b^3G'_3$...	45563.00						$a^5F'_2$....	7985.792	a^3H	a^7P	a^7D'	a^7F
									168.931	(x)			
U′	a^3H_6...	46982.36	a^3F'	a^3G	b^3G	a^3H'		$a^5F'_1$....	8154.723				
(4)		*26.05*	a^5P'	a^5F'									
	a^3H_5...	47008.41											
		98.12											
	a^3H_4...	47106.53					U	$x^5F'_5$....	47005.498§	a^5P	a^5D'	b^5D'	a^5F
									372.457	b^5F	c^5F	a^5G'	a^3P
D	$a^5P'_3$....	17550.204§	a^5S'	a^5P	b^5P	c^5P		$x^5F'_4$....	47377.955	a^3D'	b^3F	a^3G'	a^7F
		176.814	d^5P	e^5P	a^5D'	b^5D'			*377.571*				
	$a^5P'_2$....	17727.018	c^5D'	d^5D'	b^5F	c^5F		$x^5F'_3$....	47755.526				
		200.392	a^3P	b^3P	b^3D'	c^3D'			*281.132*				
	$a^5P'_1$....	17927.410	a^3H	(x)				$x^5F'_2$....	48036.658				
									184.659				
								$x^5F'_1$....	48221.317				

TABLE II—*Continued*

Sym-bol	Type	Term	Combinations	Sym-bol	Type	Term	Combinations
L′	$y^5F'_5$....	53275.45	a^5D' b^5D' c^5D'? a^5F	J	$b^5D'_4$...	33095.961§	a^5P' a^5D y^5D a^5F'
(4)		*6.25*	b^5F c^5F a^5G' b^3F	(2)		*411.177*	x^5F' y^5F' a^3P' b^3P'
	$y^5F'_4$....	53281.70	a^3G'		$b^5D'_3$...	33507.138	x^3D y^3D z^3D a^3F'
		437.09				*294.454*	x^3F' x^3G (y)
	$y^5F'_3$....	53718.79			$b^5D'_2$...	33801.592	
		509.73				*215.532*	
	$y^5F'_2$....	54228.52			$b^5D'_1$...	34017.124	
		253.56				*104.500*	
	$y^5F'_1$....	54482.08			$b^5D'_0$...	34121.624	
Y	$a^5S'_2$....	40895.024§	a^5P' a^5D a^5F' a^3P'	Q	$c^5D'_4$...	39625.826§	a^5P' a^5D a^5F' y^5F'?
(2)			b^3P'			*344.054*	a^3P' b^3P' y^3D a^3F'
H	a^5P_3....	29056.339§	a^5P' a^5D x^5D y^5D		$c^5D'_3$...	39969.880	b^3F' b^3G x^3G (y)
		412.688	a^5F' x^5F' a^3P' x^3D			*261.492*	
	a^5P_2....	29469.027	y^3D z^3D a^3F'		$c^5D'_2$...	40231.372	
		263.718				*173.172*	
	a^5P_1....	29732.745			$c^5D'_1$...	40404.544	
						86.766	
O	b^5P_3...	36767.002	a^5P' a^5D y^5D a^5F'		$c^5D'_0$...	40491.310	
		390.594	a^3P' b^3P' x^3D a^3F'				
	b^5P_2...	37157.596		S	$d^5D'_4$...	43499.546§	a^5P' a^5D a^5F' a^3P'
		251.984				*423.170*	a^3F' b^3F'
	b^5P_1...	37409.580			$d^5D'_3$...	43922.716	
X′	c^5P_3....	42532.76	a^5P' a^5D a^5F' a^3P'			*260.958*	
(3)		*327.06*	a^3F' b^3F'		$d^5D'_2$...	44183.674	
	c^5P_2....	42859.82				*227.45*	
		219.23			$d^5D'_1$...	44411.12	
	c^5P_1....	43079.05				*47.76*	
					$d^5D'_0$...	44458.88	
a	d^5P_3...	46137.10	a^5P' a^5D a^3P' b^3P'				
(1)		*176.50*		G	a^5F_5....	26874.560§	a^5D x^5D y^5D a^5F'
	d^5P_2...	46313.60				*292.276*	x^5F' y^5F' x^3D y^3D
		96.82			a^5F_4....	27166.836	z^3D a^3F' x^3F' x^3G
	d^5P_1...	46410.42				*227.861*	x^7D (y)
U″	e^5P_3....	47966.53	a^5P' a^5D a^5F' a^3P'		a^5F_3....	27394.697	
(3)		*196.89*	b^3P'			*164.894*	
	e^5P_2....	48163.42			a^5F_2....	27559.591	
		126.36				*106.767*	
	e^5P_1....	48289.78			a^5F_1....	27666.358	
F	$a^5D'_4$...	25900.001§	a^5P' a^5D x^5D y^5D	K	b^5F_5...	33695.418§	a^5P' a^5D x^5D y^5D
		240.187	a^5F' x^5F' y^5F' x^3D			*344.119*	a^5F' x^5F' y^5F' a^3P'
	$a^5D'_3$...	26140.188	y^3D z^3D a^3F' x^3F'		b^5F_4...	34039.537	x^3D y^3D z^3D a^3F'
		199.518	x^3G x^7D (y)			*289.237*	b^3F' x^3F' x^3G (y)
	$a^5D'_2$...	26339.706			b^5F_3...	34328.774	
		139.685				*218.457*	
	$a^5D'_1$...	26479.391			b^5F_2...	34547.231	
		71.101				*144.941*	
	$a^5D'_0$...	26550.492			b^5F_1...	34692.172	

TABLE II—*Continued*

Sym-bol	Type	Term	Combinations	Sym-bol	Type	Term	Combinations
R (2)	c^5F_5....	40257.290	a^5P' a^5D y^5D a^5F'	X (2)	x^7D_5...	42815.849§	a^7P a^7D' a^7F a^5D'
		337.093	x^5F' y^5F' a^3P' x^3D			*347.475*	a^5F
	c^5F_4....	40594.383	$y^3D?$ z^3D a^3F' b^3F'		x^7D_4...	43163.324	
		247.762	x^3G (y)			*271.308*	
	c^5F_3....	40842.145			x^7D_3...	43434.632	
		175.883				*198.900*	
	c^5F_2....	41018.028			x^7D_2...	43633.532	
		112.620				*130.444*	
	c^5F_1....	41130.648			x^7D_1...	43763.976	
L (2)	a^5G_6'...	34843.976§	a^5D a^5F' x^5F' y^5F'	W (2)	a^7P_4....	23711.467§	x^7D a^5D x^5D a^5F'
		−61.530	z^3D a^3F' b^3F' x^3F'			*469.410*	(y)
	a^5G_5'...	34782.446	b^3G x^3G a^3H' (y)		a^7P_3....	24180.877	
		474.896				*326.048*	
	a^5G_4'...	35257.342			a^7P_2....	24506.925	
		354.304					
	a^5G_3'...	35611.646		E	a^7D_5'...	19350.895§	x^7D a^5D x^5D a^5F'
		244.776				*211.565*	(y)
	a^5G_2'...	35856.422			a^7D_4'...	19562.460	
						194.584	
X'' (3)	b^5G_6'...	42784.35	a^5F' a^3F' b^3F' b^3G		a^7D_3'...	19757.044	
		127.56	a^3H'			*155.462*	
	b^5G_5'...	42911.91			a^7D_2'...	19912.506	
		111.11				*107.140*	
	b^5G_4'...	43023.02			a^7D_1'...	20019.646	
		114.52					
	b^5G_3'...	43137.54		V (2)	a^7F_6....	22650.422§	x^7D a^5D x^5D a^5F'
		72.47				*195.456*	x^5F' (y)
	b^5G_2'...	43210.01			a^7F_5....	22845.878	
						150.806	
t (1)	c^5G_6'...	45608.31	a^5D a^5F' a^3F' b^3F'		a^7F_4....	22996.684	
		-17.73	a^3G b^3G a^3H'			*114.261*	
	c^5G_5'...	45726.04			a^7F_3....	23110.945	
		107.09				*81.556*	
	c^5G_4'...	45833.13			a^7F_2....	23192.501	
		80.37				*52.344*	
	c^5G_3'...	45913.50			a^7F_1....	23244.845	
		51.34				*25.544*	
	c^5G_2'...	45964.84			a^7F_0....	23270.389	

MISCELLANEOUS TERMS

$ay_{6?}$	.....	50342.20	a^7D' a^7F	iy_4	.....	50833.40	
by_5	.....	50377.96		jy_3	.....	50861.45	
$cy_{5,4}$	.....	50423.00	a^7P a^7D' a^7F	ky_2	.....	50884.31	a^7P a^7D' a^7F
dy_5	.....	50475.20		ly_2	.....	50998.63	
ey_3	.....	50534.26		my_1	.....	51048.05	
$fy_{3,2}$	.....	50638.75	a^7P a^7D'	ny_2	.....	51070.77	
gy_5	.....	50703.72	a^7P a^7D' a^7F	oy_1	.....	51091.70	a^7D' a^7F
hy_5	.....	50802.68	a^7D' a^7F				

TABLE II—*Continued*

Symbol	Type	Term	Combinations	Symbol	Type	Term	Combinations
py_3	.....	51148.80	a^7P a^7D' a^7F	bx_3	.....	46745.01	a^3P' a^3F' b^3F' a^3G b^3G a^3H' a^5P' a^5F'
$qy_{4,3}$	.....	51192.35					
ry_2	.....	51208.05					
$sy_{3,2}$	.....	51329.11	a^7D'	cx_2	.....	46888.53	a^3P' a^3F' b^3F' b^3G a^5P' a^5F'
ty_3	.....	51334.89	a^7P a^7D' a^7F				
uy_6 (4)	.....	53169.23	a^3G' a^5F b^5F c^5F a^5G'	dx_4	.....	46889.12	a^3F' b^3F' a^3G b^3G a^3H' a^5P' a^5F'
vy_5 (1)	.....	53414.50	a^3G' a^5G'	ex_3	.....	47092.71	a^3P' a^3F' b^3F' a^3G b^3G a^3H' a^5P'
wy_4	.....	53417.04	b^3F a^3G' a^5G'	fx_1	.....	47177.24	a^3P' a^3F' b^3F' a^5P' a^5F'
xy_3 (4)	.....	53617.62					
yy_4	.....	53769.00	a^3D' b^3D' a^3F b^3F	gx_2	.....	47197.03	a^3P' a^3F' b^3F' a^3G b^3G a^5P' a^5F'
zy_3	.....	54161.19	a^3G' a^5D' b^5D' c^5D'	hx_6	.....	49434.20	a^3G b^3G a^3H'
$a'y_2$ (1)	.....	54375.60	a^5F b^5F a^5G'	ix_5	.....	49460.95	a^3F' b^3F' a^3G b^3G a^3H'
				jx_4	.....	49727.04	
ax_4	.....	46720.84	a^3F' b^3F' a^3G b^3G a^3H' a^5P' a^5F'	kx_3 (4)	.....	49850.65	a^3P' a^3F' b^3F' a^3G b^3G a^3H'

NOTES TO TABLE II

(1) Walters, unpublished material.
(2) Meggers, *Astrophysical Journal*, **60**, 60, 1924.
(3) Laporte, *Proceedings of the National Academy of Sciences*, **12**, 496, 1926, and unpublished material.
(4) Russell, unpublished material.
§ Babcock, improved term values from unpublished material.

greater than ± 0.05 A has been included. All lines whose measures fall within this margin are indicated with a dagger in Table I.

For the convenience of those who are working on this complex spectrum, a list of all the known terms of *Fe* I is given in Table II. Here all term values are counted upward from zero level a^5D_4. Several new terms are included, some of which have been found by Russell, and others by F. M. Walters, Jr., who has kindly consented to their publication in this paper. The letters in the first column indicate the arbitrary symbols which have heretofore been applied to the term. The numbers in this column refer to notes at the end of the table giving the source from which the term has been taken. When no number is given the term is listed by Walters.[1] The second column states the type of the term according to the standard

[1] *Journal of the Optical Society of America*, **8**, 245, 1924.

spectroscopic notation. Here the terms are in the order: triplets, quintets, septets, the "even" sets of terms S, P′, D, F′, G, H′, preceding the "odd" S′, P, D′, F, G′, H, for each type. Terms for which the type is not assigned are at the end of the table. While some of the letters a, b, c, x, y, etc., may be changed as the analysis of the spectrum progresses, the types are known in most cases, and a uniform notation seems desirable.

The notation for those energy-levels which have not been classified as components of multiple terms is purely provisional, *ad interim*, ay, by, cy denoting "even," and ax, bx, cx "odd," levels. As practically the whole alphabet had already been used in the chaos of arbitrary designations of known terms, these combinations of lower-case letters were unavoidable. They are adopted from necessity, not as models for imitation. When determined, the inner-quantum number is given as a subscript.

The third column gives the term values and interval separations, the latter in italics. The symbol § indicates improved values derived by H. D. Babcock on the basis of his measures of the iron standards on the neon scale. With the exception of $d^5D'_1$, $d^5D'_0$, $x^5F'_5$, and y^5D_0, he has determined values for each component of the groups marked with this symbol.

The last column gives the known combinations of each term. Here inter-system combinations follow all others, and parentheses indicate, as in Table I, that the type of term has not been determined. Since many faint *Fe* lines have never been measured, it is highly probable that more faint combinations might be found among the solar lines. The present incomplete work has been done, however, in the hope that it may be of use in further astrophysical investigation.

In conclusion the writers wish to express their thanks to Messrs. St. John, Babcock, and King for their advice and co-operation, to Mr. E. F. Adams for assistance with the measuring, and to all who kindly permitted their unpublished material to be included in this paper.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
June 1, 1928

AN OPTICAL OSCILLOGRAPH[1]

By SINCLAIR SMITH

ABSTRACT

A beam of light, after passing through a nicol prism, a quartz plate (perpendicular to the axis), a CS_2 cell, and a second nicol, is photographed with a rotating-mirror spectrograph. The current to be studied is carried by a solenoid which surrounds the CS_2 cell. The first nicol renders the light plane-polarized, the quartz plate rotates the plane of polarization, and the CS_2 cell adds to, or subtracts from, the rotation, depending on the current through the solenoid. The second nicol removes from the beam all wave-lengths which have suffered a rotation of $n\pi$, where n is an integer. Thus, if the light coming through the second nicol is viewed through a spectroscope, the spectrum is seen to consist of a series of bright and dark bands, the position of the dark bands depending on the current through the solenoid. If the light is photographed with a rotating-mirror spectrograph while a non-uniform current is flowing through the solenoid, the fluctuations of the current are reproduced on the film.

During the progress of work on condenser discharges, the need arose for an oscillograph capable of recording transients having periods in the range from 2×10^{-5} to 10^{-6} seconds. Mechanical systems for such high frequencies are out of the question, and cathode-ray oscillographs, although capable of furnishing excellent records, require a very elaborate set-up when used to record transients. By making use of the fact that the plane of polarization of a beam of light traversing a dense medium can be rotated by a magnetic field, it was found possible to construct an optical oscillograph which served satisfactorily for the problem at hand and which may be of use in other fields.[2]

The arrangement of parts is shown in Figure 1. Light from a spark is rendered parallel by the lens L_1 and plane-polarized by the first nicol. The light next passes through a quartz plate (cut perpendicular to the optic axis) which rotates the plane of polarization, the rotation varying with the wave-length according to the relation

$$\theta=A+\frac{B}{\lambda^2}.$$

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 366.

[2] Shortly after this work was completed, Professor Frederick Bedell called my attention to the fact that an almost identical scheme was devised and applied by A. C. Crehore in 1894; see *Transactions of American Institute of Electrical Engineers* for October, 1894. The method is fully described in *The New Polarizing Photo Chronograph*, by A. C. Crehore and George O. Squier (John Wiley & Sons, 1897). Since this work may not now be generally available, it seems worth while to give a complete description of the method.

Thus the light after passing through the quartz plate has suffered rotatory dispersion. The dispersion used, that given by a plate 5 cm thick, was such that λ 5300 was rotated two complete turns; λ 4500, three turns; and λ 3950, four turns.

The light next passes through a carbon bisulphide cell about which is wound a solenoid which carries the current to be studied. When a current flows through this solenoid a magnetic field is set up within the cell and the carbon bisulphide acquires the property of producing additional rotatory dispersion. This additional disper-

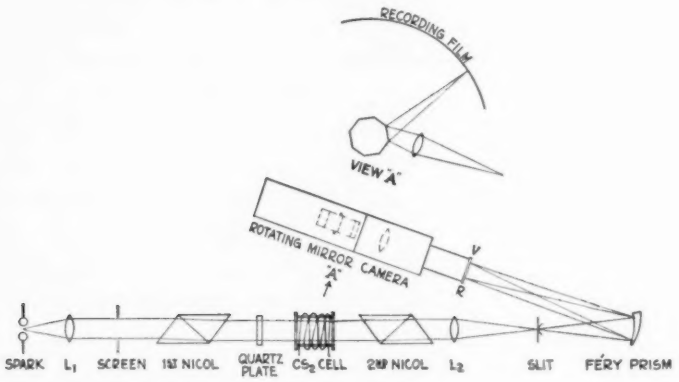


FIG. 1.—Diagram of apparatus

sion, depending on the direction of the current, may either add to or decrease the dispersion produced by the quartz. For our purposes, therefore, we may imagine that the current simply changes the thickness of the quartz.

This dispersed light next passes through the second nicol, which removes from the beam those wave-lengths whose plane of polarization corresponds to the "crossed" position of the nicol. The unobstructed light is brought to a focus on the slit and resolved by the Féry[1] prism into a spectrum, which consists of a series of bright and dark bands, the dark bands corresponding to the spectral regions cut out by the second nicol. If a current is now sent through the solenoid, the dark bands move toward either the red or the violet, for, as we have seen, the current effectively changes the thickness of

[1] *Astrophysical Journal*, **34**, 79, 1911.

the quartz and this in turn determines which wave-lengths receive the proper rotation to be cut out by the second nicol.

The records are made with the rotating-mirror camera.[1] With this instrument, a narrow spectrum is projected on and moved along the recording film at some predetermined speed, thus furnishing a time scale. As the position of the bands in the spectrum is determined by the current passing through the solenoid, we have a combination that records the value of the current against the time scale.

The scale along the current axis is not perfectly linear, but, provided the optical rotation produced by the quartz is made several times that produced by the current and a prism is used to form the spectrum, the departure from linearity is small. The prism is necessary to compensate for the dispersion of the quartz plate. As the quartz plate rotates the shorter wave-lengths more than the longer, the difference in wave-length between successive dark bands (regions that have suffered a rotation of $n\pi$ radiants, n being an integer) decreases toward the violet. In a normal spectrum the bands would therefore be unequally spaced. If the spectrum is formed by a prism, however, this inequality in spacing is largely compensated by the increase in dispersion toward shorter wave-lengths and the linear distance between bands becomes very nearly constant. This is obvious when one recalls that both the rotatory dispersion of quartz and the linear dispersion of a prism follow a law of the same form; namely,

$$\text{Dispersion} = A + \frac{B}{\lambda^2}.$$

In the set-up used to study condenser discharges, 1-inch nicols were used. The quartz plate was 5 cm thick, and the carbon bisulphide cell was 3 cm in diameter and 5 cm long. The solenoid consisted of six turns of No. 14 rubber-covered wire, wound around the cell. For some of the work the discharge spark of the condenser being studied served as a light source, but, in general, a fine tungsten wire placed in series with the spark was used. When the discharge passed, the wire "exploded," furnishing more than sufficient light.

[1] *Mt. Wilson Contr.*, No. 323; *Astrophysical Journal*, **64**, 300, 1926.

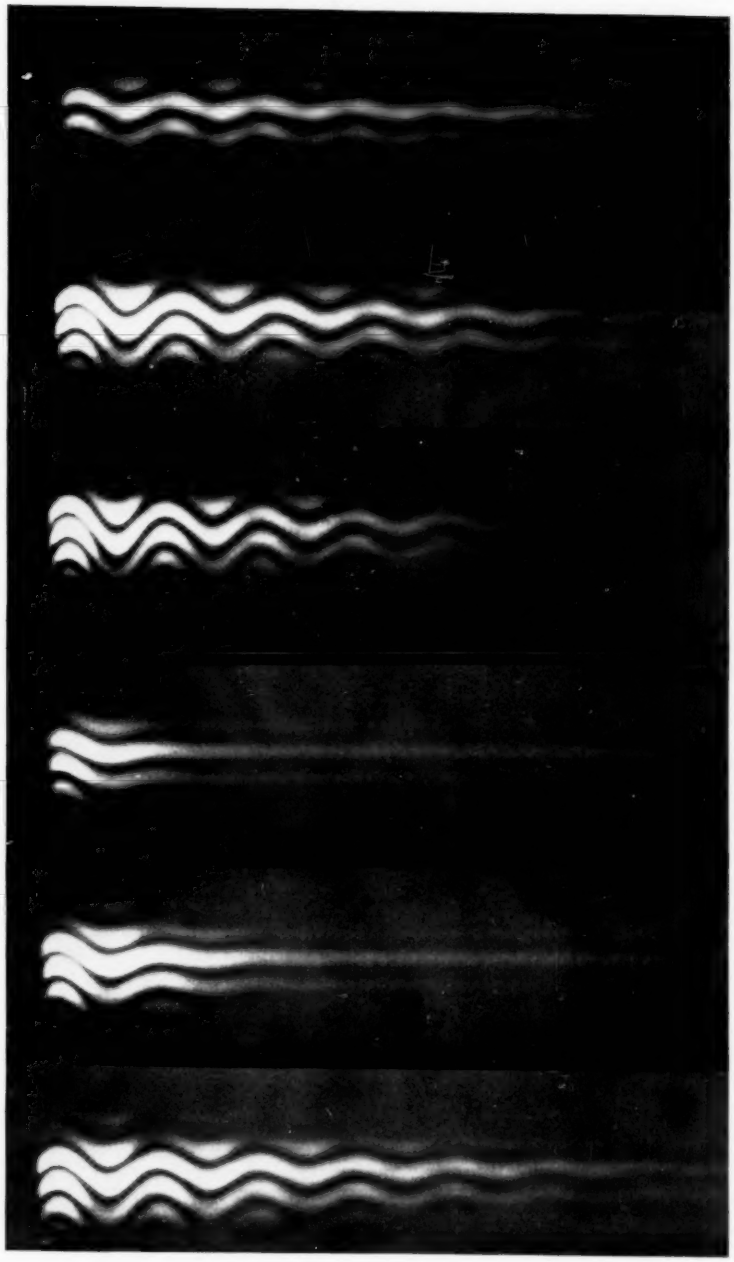
The condenser had a capacity of 2 microfarads and could be charged to 35,000 volts.

Some typical oscillograms are shown in Plate IV. The group marked *a*, *b*, and *c* shows the behavior at three different voltages. When these were taken, the condenser discharged at 15,000, 25,000, and 35,000 volts, respectively. The frequency is the same for all three, being about 60,000 cycles per second. The oscillograms marked *d*, *e*, and *f* show the effect of a resistance in the circuit. The first, marked *d*, was taken with 1 ohm in series with the spark, which, as can be seen, is almost critical for this circuit. The next, *e*, was taken with $\frac{1}{2}$ ohm inserted, while in the case of *f*, only the inherent damping of the spark and circuit leads was present.

No attempt was made at calibration. Current values were merely computed from the well-known expression for the current in a condenser discharge. In case more accurate values of the current are required, a series of solenoids may be used, which would allow a direct comparison with a steady current. The best method to be used, however, will in general be determined by the conditions of the particular problem at hand.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
June 1928

PLATE IV



TYPICAL OSCILLOGRAMS

a, *b*, *c*.—The effect of differences in voltage
d, *e*, *f*.—The effect of adding resistance to the circuit

UNIV. OF

ON THE VARIATION OF THE RADIAL VELOCITY OF TU CASSIOPEIAE[1]

By ROSCOE F. SANFORD

ABSTRACT

Fifty-nine spectrograms of TU Cassiopeiae obtained between 1917 and 1928 furnish the data with which to relate the variation in radial velocity to the light-curve and the two available epochs of maximum light. On the assumption that light-maximum and velocity-minimum coincide, the usual relations of light-curve and radial-velocity variation for Cepheid variables are best expressed by the formula

Min. velocity (max. light) = J.D. $2421503.158 + 2^{d}1391E + 0^{d}259\ (10^{-3}E)^{2}$ (G.M.T.)

Although the representation is better than that given by a formula of a constant period, the irregularity in the resulting plot of the velocities suggests that superposed changes in the period or in the shape of the velocity-curve may be present.

It is noteworthy that certain kindred irregularities in light are known to exist and that the period of TU Cassiopeiae is unusual in that it falls in the minimum of the frequency-curve of periods for Cepheids as a class.

THE LIGHT-CURVE

The variability of B.D. $+50^{\circ}72$[2] was discovered by Miss Cannon[3] from an examination of plates of the Harvard College Observatory. She found that the range of magnitude is between 7.2 and 8.6 and that the period appeared to be short. The star's designation became TU Cassiopeiae.

Zinner,[4] from his first observations, derived the formula

$$\text{Max. light} = \text{J.D. } 2419244 + 59^{d}E \text{ (G.M.T.) with } M - m = 33^{d}.$$

His later observations,[5] in 1911 and 1912, did not, however, confirm this long period.

Van Biesbroeck and Casteels,[6] from their observations in 1911 and 1912, obtained a light-curve with the aid of the formula

$$\text{Max. light} = \text{J.D. } 2419302.12 + 2^{d}139E \text{ (G.M.T.)}.$$

The range of magnitude of their curve, shown at the bottom of Figure 1, is 7.3 to 8.4; minimum precedes maximum by $0^{d}54$, and

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 367.

[2] H.D. 2207; A.G. Cambridge 172; $\alpha = 0^{h}20^{m}9$, $\delta = +50^{\circ}43'$ (1900); μ (Wilson) $0''.80$.

[3] *Harvard Circular*, No. 164, 1911.

[4] *Astronomische Nachrichten*, **190**, 378, 1912.

[5] *Ibid.*, **195**, 454, 1913.

[6] *Annales de l'Observatoire Royal de Belgique* (2), **13**, 185, 1914.

a slight secondary maximum follows it by $0^d.63$. They concluded that the star is a Cepheid variable.

R. H. Baker,[1] from observations in 1912, represented maximum light by

$$\text{J.D. } 2419631.8+2^d.137E \text{ (G.M.T.)}.$$

These seem to comprise the published data for the light-curve and point to Cepheid variation in a short period, such as Miss Cannon surmised.

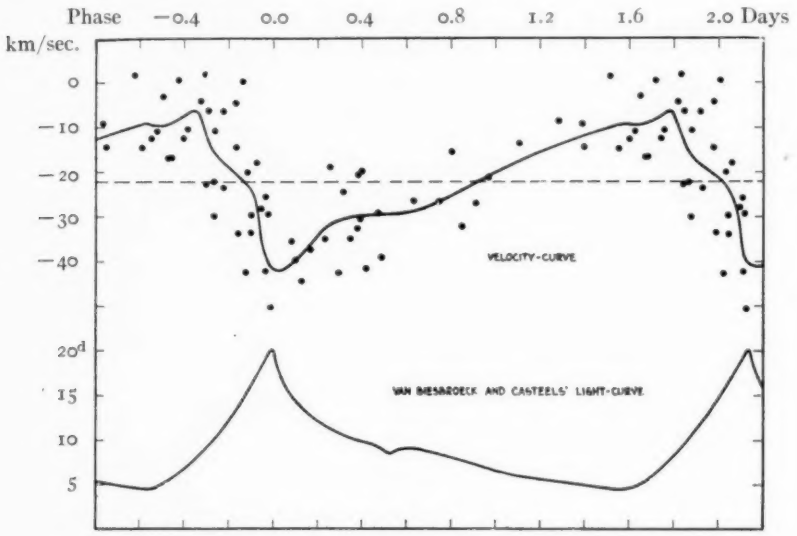


FIG. 1.—The individual velocities for TU Cassiopeiae, the mean velocity-curve, and the velocity of the system are shown above. The ordinates for the mean light-curve below are arbitrary steps as used in Argelander's method of observing variables.

THE SPECTRUM AND RADIAL VELOCITY

According to Miss Cannon, the spectral class of TU Cassiopeiae is G0. Shapley,[2] from objective-prism spectrograms, finds a variation in spectrum from F1 to F8.

Fifty-nine slit spectrograms were made with the 60-inch (γ series) and 100-inch (C series) reflectors between September, 1917,

[1] *Laws Observatory Bulletin*, **2**, 69 (No. 20), 1913.

[2] *Mt. Wilson Contr.*, No. 124; *Astrophysical Journal*, **44**, 6, 1916.

and February, 1928. Table I gives the data of observation and measurement, each velocity being the mean of at least two measures. The median spectral class on the Mount Wilson system is F4.

Van Biesbroeck and Casteels' period was used to assemble the fifty-nine values of the radial velocity. The plot shows that if phases are to be reckoned with a constant period, this period needs very little change. In the end, the best representation was obtained with the formula

$$\text{Minimum velocity} = \text{J.D. } 2421503.026 + 2^{d}.1395E \text{ (G.M.T.)},$$

the epoch being the one closest to the first observation of radial velocity. On the assumption that maximum light and minimum velocity coincide, the representation of the epochs of light-maximum by Van Biesbroeck and Casteels and by Baker given by this formula is as follows:

	Observed	Computed	O−C	*E*
Van Biesbroeck and Casteels.....	J.D. 2419302.12	9301.511	$+0^{d}.61$	−1029
Baker.....	9631.8	9630.990	+0.8	− 875

These excessive residuals could be removed by increasing the epoch of the formula by $0^{d}.710$, by shortening the period by $0^{d}.00075$, or by adjusting both epoch and period; but the radial velocities will not admit of such changes, if those velocities which fall on the very steep descending branch of the velocity-curve are to be best harmonized with a constant period.

An examination of the plotted radial velocities suggested that the period may be slowly increasing. Numerous trials gave in the end the following formula

$$\text{Min. velocity (max. light)} = \text{J.D. } 2421503.158 + 2^{d}.1391E + 0^{d}.259\,(10^{-3}E)^{2}\text{(G.M.T.)}$$

as best fitting the velocities and, at the same time, satisfactorily representing the two epochs of maximum light (residuals, $-0^{d}.19$ and $+0^{d}.15$, respectively).

The phases in Table I were derived by this last formula. With these as abscissae, the velocities are plotted at the top of Figure 1.

TABLE I

OBSERVATIONS OF TU CASSIOPEIAE

Plate No.	Date	G.M.T.	Phase	Vel.
				km/sec.
γ 6239....	1917 Sept. 30	23^h44^m	$1^d.971$	− 4.3
6283....	Oct. 7	20 45	0.290	−42.8
6360....	Nov. 4	18 15	0.376	−32.5
7768....	1919 Jan. 15	16 20	0.909	−26.9
C 805....	1920 Dec. 18	16 17	0.080	−35.6
1917....	1922 Oct. 3	21 02	1.741	−12.4
1921....	4	21 45	0.633	−26.8
γ 11358....	5	20 50	1.595	−12.4
11364....	6	21 36	0.487	−39.2
11459....	Dec. 5	19 00	0.471	−29.2
C 2036....	1923 Jan. 1	15 58	1.671	−16.7
γ 11500....	3	15 38	1.518	+ 1.4
C 2326....	June 26	23 20	0.392	−30.4
2331....	27	23 25	1.396	−14.4
γ 11904....	28	23 18	0.252	−18.9
12003....	Aug. 4	22 26	0.843	−32.4
12008....	5	22 12	1.833	+ 1.9
C 2427....	Sept. 2	18 41	1.871	−10.5
2434....	4	19 12	1.753	−10.8
2437....	4	23 08	1.917	− 6.5
2455....	26	19 28	0.228	−35.0
2477....	Oct. 3	17 55	0.745	−26.6
2494....	21	19 05	1.676	−16.8
γ 12246....	28	20 10	0.162	−37.4
12250....	29	18 44	1.102	−13.6
12258....	30	19 04	2.118	−50.6
C 2548....	Nov. 22	18 20	1.551	−14.9
γ 12788....	1924 July 13	22 56	0.379	−20.5
12794....	14	23 02	1.384	− 9.2
C 2881....	16	23 54	1.279	− 8.6
γ 12942....	Sept. 10	23 56	1.648	− 3.0
12945....	11	21 45	0.417	−41.6
C 3005....	13	22 29	0.311	−24.5
γ 13023....	Oct. 15	16 40	2.111	−29.2
13036....	17	18 49	2.060	−17.8
C 3062....	19	17 02	1.846	− 6.2
3065....	19	21 39	2.038	−29.6
γ 13627....	1925 Aug. 6	21 0	2.004	+ 0.4
13634....	8	22 18	1.919	−23.6
13638....	9	22 45	0.799	−15.5
13739....	Sept. 24	19 06	1.711	+ 0.4
C 3589....	Dec. 3	15 54	0.964	−21.2
3597....	6	15 45	1.817	− 4.2
3899....	1926 July 23	21 47	2.105	−42.0
γ 14426....	Aug. 15	23 05	1.621	−11.0
14429....	16	21 01	0.395	−20.0
C 3958....	18	23 06	0.343	−34.8
4057....	Oct. 21	16 44	2.020	−42.6
4061....	21	22 31	0.122	−44.3
γ 14632....	23	22 05	2.104	−25.6
14732....	Nov. 20	14 34	1.972	−14.3
15172....	1927 Aug. 10	20 07	1.989	−33.3

TABLE I—*Continued*

Plate No.	Date	G.M.T.	Phase	Vel.
				km/sec.
γ 15179....	1927 Aug. 12	20^h25^m	1^d863	−22.1
15193....	14	23 20	1.844	−22.8
C 4428....	Sept. 11	19 44	1.876	−29.8
4430....	11	23 40	2.040	−33.6
γ 15285....	Oct. 9	20 41	2.098	−27.6
15288....	10	00 00	0.092	−39.0
C 4669....	1928 Feb. 6	15 19	2.031	−20.3

The curve through the observations was obtained by connecting thirteen normal points formed by combining the individual velocities in order of phase into groups of from three to six, according to the rapidity of change of velocity. The broken horizontal line shows the velocity of the system, −22.2 km/sec., the mean of the 59 velocities in Table I. This mean curve indicates a progressive change in radial velocity throughout the adopted period and parallels the light-curve in the manner characteristic of Cepheid variation. The coincidence of light-maximum and velocity-minimum has, in a sense, been artificially imposed. This, however, is justified by the overwhelming evidence from other Cepheids, observed both photometrically and spectroscopically, and by the fact that minimum exposure times were necessary for spectrograms that yielded minimum velocities.

The spectrum of TU Cassiopeiae shows the enhanced lines of numerous elements which are characteristic of Cepheid variables. These lines undergo the usual transformation from greatest strength near minimum velocity to least strength near maximum velocity, but their quality at all times is such that at least the normal accuracy pertaining to stellar spectra of this type and dispersion would be anticipated. Nevertheless, the scattering of the values displayed in the plot, if ascribed wholly to errors in the velocities, evidently points to a far lower precision than usual. Experience with numerous spectroscopic binaries and with stars of constant velocity scarcely admits of the existence of such exceptional errors in the present case.

Obvious possibilities of explanation are periodic changes in (1) the velocity of the system; (2) the shape of the velocity-curve; (3)

the period. Considerable time has been spent in attempts to improve the representation by changes of this kind, but with no satisfactory result. If changes are present, the distribution of the observations is not such as to reveal them. A satisfactory investigation of these possibilities would require a great number of carefully placed radial velocities, a demand not easily satisfied under the conditions of observing at Mount Wilson. It has therefore been decided to discontinue the observations.

It is unfortunate that more has not been done on the light-curve of TU Cassiopeiae, especially since Van Biesbroeck and Casteels[1] found irregularities in the variation and, in particular, considerable scattering in the magnitudes near the epochs of maximum and minimum light. This is akin to the pronounced scattering of the velocities around the times of minimum and maximum velocity.

A point which may be significant is that the curve of period-frequency[2] for Cepheid variables has a minimum for periods near that of TU Cassiopeiae. The deficiency seems to be real, for there is no apparent reason why variability in such a period should more readily fail of detection than that having shorter or longer periods. Since the avoidance of such periods probably has some physical explanation, it is possible that the rare cases, such as TU Cassiopeiae, might show some evidence of instability, as, for example, the failure to attain the same values of light and velocity at successive maxima and minima of light.

In conclusion, it seems safe only to state:

a) The 59 radial velocities already obtained give evidence of a mean variation in a slowly increasing period, which is related to the mean light-variation in the manner usual with Cepheids.

b) These values, pertaining to about 50 distinct epochs scattered over more than 1700 cycles of light-variation, indicate that the velocity does not vary in any simple uniform fashion, but undergoes modifications which the data appear insufficient to unravel.

c) Under the circumstances it appears futile to derive elements for the variation of velocity except perhaps to give, as the most likely value of the velocity of the system, the mean of the 59 velocities,

[1] *Annales de l'Observatoire Royal de Belgique* (2), **13**, 186, 1914.

[2] *Handbuch der Astrophysik*, **6**, 193, 1928.

which is -22.2 km/sec., and to trace a mean curve of velocity-variation as in Figure 1.

The anomalies in both light-curve and velocity-curve and the rather unusual period of TU Cassiopeiae make the star of exceptional interest and emphasize the necessity for further photometric study, which it is hoped will be undertaken by precise methods in the near future.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
May 1928

PREPARATION OF ABSTRACTS

Every article in the *Astrophysical Journal*, however short, is to be preceded by an abstract which should be submitted by the author with the manuscript. In order that the abstract may aid the reader by furnishing an index and brief summary of the contents of the article, and may also be suitable for reprinting in an abstract journal, it should be of the type of those which have been appearing in the *Astrophysical Journal* since 1920. It is requested that the abstracts be prepared in accordance with the following:

DIRECTIONS AND RULES

1. *Notes.*—Read the article carefully, taking rough notes covering all the new information reported, keeping a specially sharp lookout for new incidental results and suggestions not directly related to the main subject.

Material not new need not be described; a valuable summary of previous work, however, should be noted.

2. *Subtitles.*—Write, first, a title describing the group of results forming the main contribution of the article, including all that belong together. If there are in addition results which do not come under that title, gather them into as few groups as possible and formulate a complete and precise title for each.

The subtitles should together form a complete index of the new information; that is, they should include every measurement, observation, method, suggestion, and theory which is presented as new and of value in itself. They should be complete in themselves and independent of the main title of the article.

3. *Text.*—Write a paragraph summarizing the main group of results and including the corresponding subtitle either all at the beginning or with parts scattered through the text; and then do likewise for the other groups.

A separate paragraph should be used for each distinct subject involved, but no more than necessary. All material which can easily be grouped together under a single title should be summarized in the same paragraph. Parts of subtitles may be scattered through the text, but the subject of each paragraph must be given at the beginning.

The text should summarize the author's conclusions and should transcribe all numerical results of general interest, including all that might be looked for in a table of astronomical and physical constants, with an indication of the accuracy of each. It should give all the information that anyone not a specialist in the particular field involved might care to have in his notebook.

Complete sentences should be used except in the case of subtitles. The abstract should be made as readable as the necessary brevity will permit. Italicize subtitles but no other words or phrases.

4. *Final checking.*—Re-read the article so as to check the abstract and correct any omissions and mistakes; read the subtitles by themselves to see that they properly index the information; and read the abstract to see whether it cannot be condensed and its English be improved.